ILLUMINATING ENGINEER

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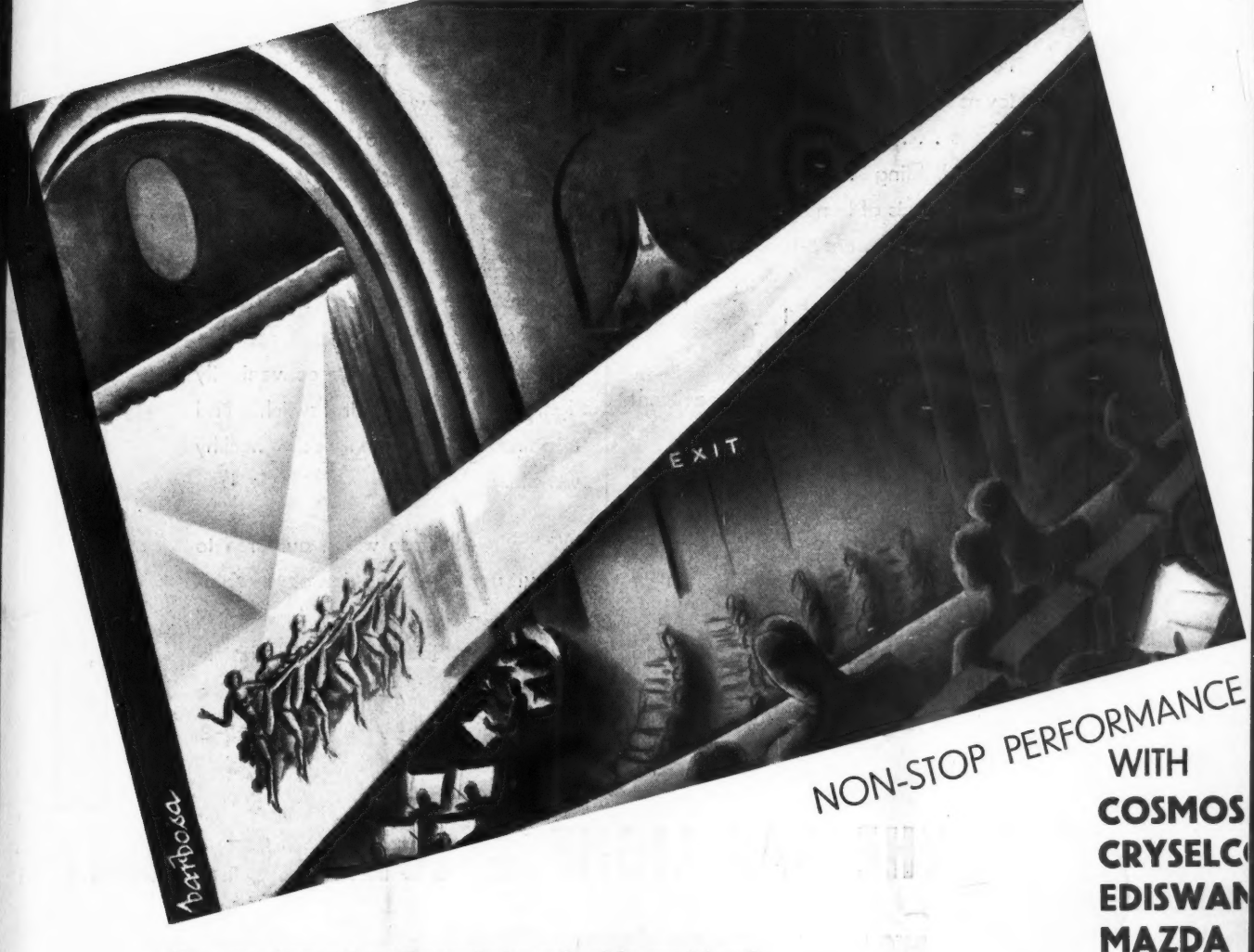

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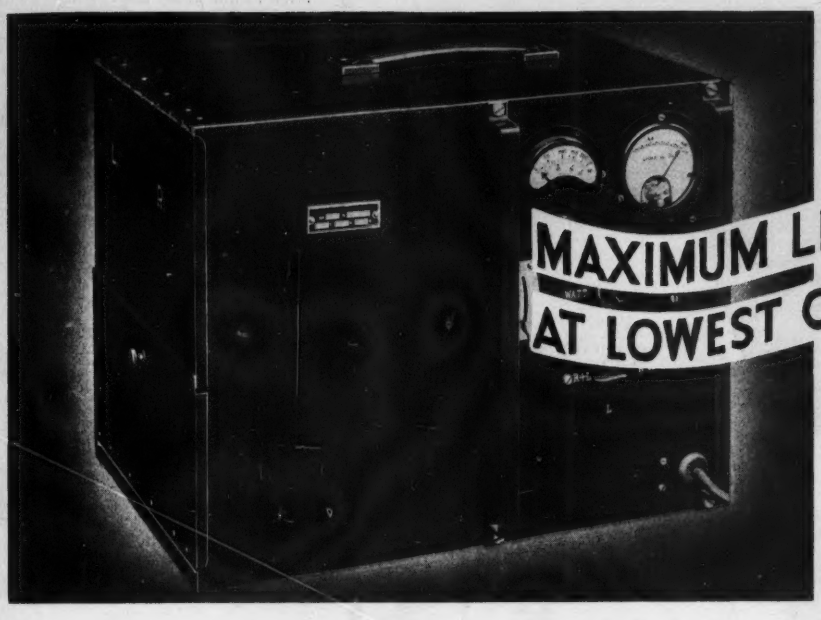

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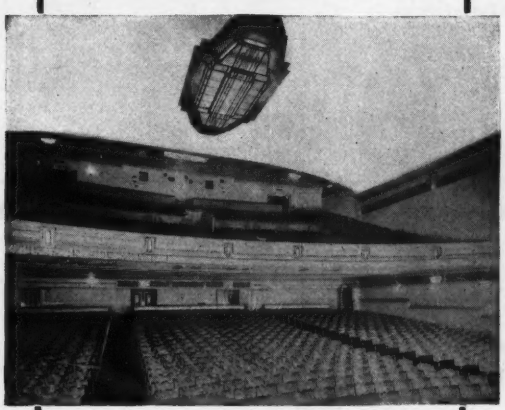

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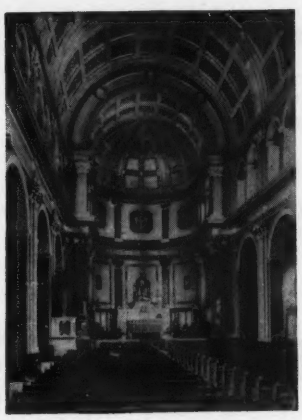

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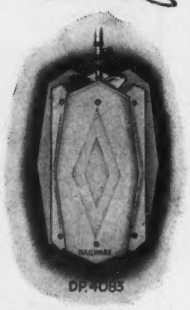
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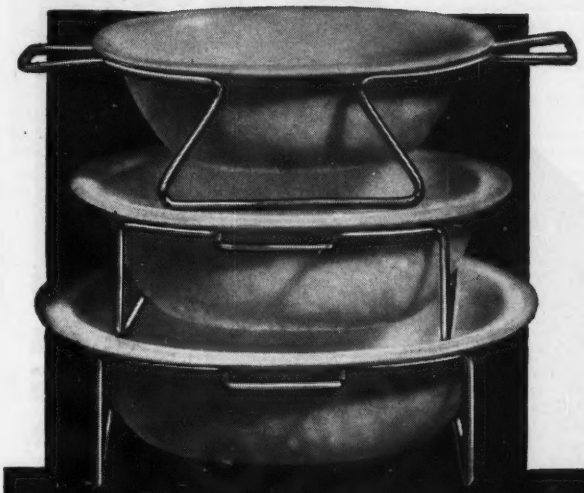

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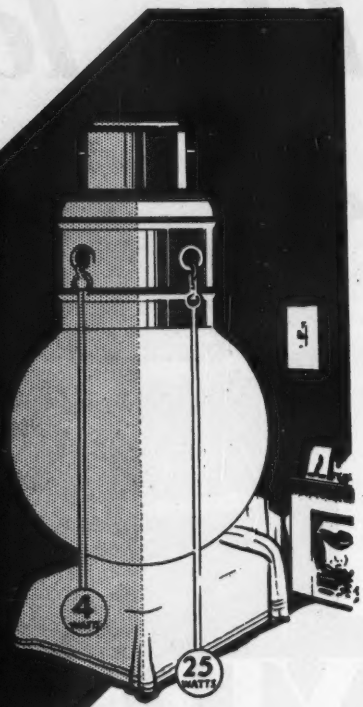

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The Specification and Manufacture of Opal Glass

THE joint meeting of the Illuminating Engineering Society and the Society of Glass Technology, on December 13th, was the first combined gathering of the kind arranged by the two societies. By general consent it was a most successful one, which we hope will be repeated.

Glass of various kinds tends to enter more and more into illuminating engineering, and the particular variety discussed at this meeting—opal glassware—offers a particularly good field for study. The three contributions, by Dr. S. English, by Mr. Ryde and his colleagues at Wembley, and by Dr. Hampton, which are concluded in this issue, together contained an excellent review of the whole problem. The essential items were defined, the work of the B.I.S. Committee leading to the analysis and specification of opal glassware was summarized and the manufacturing difficulties pointed out.

Broadly speaking, illuminating engineers demand from opal glassware that the surface of the glassware should not be "patchy," but should have reasonably uniform brightness, that the shape of the filament or mantle should not be visible through the globe, and that the absorption of light should not be excessive.

Uniformity of brightness and invisibility of the source, both characteristic of good diffusion, usually go together. There is no great difficulty in securing *either* good diffusion of light or reasonably good transmission (although during the war globes offending in both respects were not infrequently met with!) but it is less easy to satisfy both requirements. Added to this main problem we have the consideration whether cased opal or pot opal glass should be used, and the complexities arising from defects of manufacture such as varying thickness of glass or irregular distribution of particles.

It is, therefore, greatly to the credit of the workers whose investigations are now described that they have not merely analysed the part played by such qualities as thickness of material, number of particles per unit volume, size of particles and characteristic scattering effect, but have also developed the basis of a specification for opal glassware.

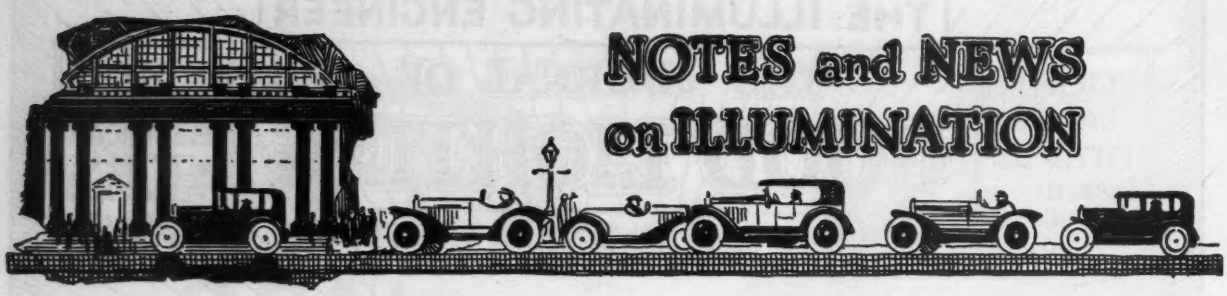
Research in the Gas Industry

THE visit of members of the Illuminating Engineering Society to Watson House, one of the main research centres of the gas industry, on January 10th, proved to be an admirable supplement to the visit to the G.E.C. Research Laboratory at Wembley in November last.

It was, we believe, a revelation to some of the visitors to learn of the variety of research constantly in progress at Watson House, which also serves as a training centre for employees of the Gas Light and Coke Company. The fact that much of this experimental work did not relate to lighting, but to such matters as the design of heating and cooking equipment, the analysis of flue-products and the prevention of corrosion of pipes, was no drawback. No one could fail to be impressed by the number of considerations, apart from purely technical aspects of lighting, that are involved in the average gas installation. One illustration of this was afforded by a new form of lighting unit, which offers to factory owners the inducement of itself affording adequate heating, providing that an illumination of the order of 10 foot-candles is maintained.

One can only touch upon a few features of the work at Watson house that seemed to be of special interest, such as the research on radiation from gas fires and the experiments on ventilation and on the effect of products of combustion from modern gas appliances. It is now regarded as established that any prejudicial effects arising from the entry of such products into the atmosphere of the average properly ventilated interior are negligible. Other points of interest were the wide use made of recording instruments and the ingenuity with which electrical apparatus is often applied to purely gas research.

In conclusion, it may be added that the lighting of the workshops, offices and laboratories would serve as an object lesson to many factories. Good stage management was shown in the display of exhibits, and concealed lighting was frequently applied to reveal charts, diagrams or apparatus. The thanks of the Society are due to Mr. S. Lacey, the Sales Controller of the Gas Light and Coke Co., who welcomed the party, and to Mr. Masterman and his staff for the very considerable amount of trouble taken by them for the entertainment of the visitor.



The Illuminating Engineering Society

FORTHCOMING EVENTS.

Members are again reminded that the **Annual Dinner** is being held at the Trocadero Restaurant, Piccadilly, London, W., on **February 7th** (7 for 7-30). Any members who still desire tickets but have not yet applied for them are requested to inform the Hon. Secretary at once. These dinners, which are of an informal character—the short time devoted to speeches being afterwards followed by dancing—have proved increasingly popular during recent years. It is expected that on February 7th there will again be an excellent attendance.

The **next General Meeting** will be held in the Lecture Theatre of the Institution of Mechanical Engineers (Storey's Gate, St. James's Park, London), at 6-30 p.m., on **February 14th,** when a paper entitled **"Everyday Photometry by Photo-electric Cells"** is to be read by Dr. J. W. T. Walsh.

The General Meeting following will also be held in the Lecture Theatre of the Institution of Mechanical Engineers on March 15th, when members are looking forward to an address from Dr. Halbertsma, of Holland, reviewing developments in Illuminating Engineering abroad.

Lectures on Illumination

The complete syllabus of the course of ten lectures on illumination, which commence at the Polytechnic, Regent Street, on February 8th, appeared in our last issue. The lectures all take place at 6 p.m. on successive Wednesdays, thus terminating on April 10th. The opening lecture, by Mr. Clifford C. Paterson, is entitled "Light in the Service of Mankind." On this occasion the chair will be taken by Lieut.-Col. K. Edgcumbe, Chairman of the National Illumination Committee of Great Britain, who, like Mr. Paterson, is a Past President of the Illuminating Engineering Society. The subject matter of the lectures, each of which is to be delivered by an expert, is comprehensive and interesting. Six of the lectures will take place at the Polytechnic; for the remaining four participants in the course will have the privilege of attending the E.L.M.A. Lighting Service Bureau, Watson House, the East London College and the Home Office Industrial Museum, where special facilities for demonstrations exist, and which have been freely placed at the service of the organizers of these lectures. By the courtesy of the authorities, it is also hoped to arrange visits to the National Physical Laboratory and the G.E.C. Research Laboratories at Wembley. The fee for the complete series of lectures is £1 1s., and for individual lectures 5s. each, but persons furnished with a statement of the Head of their School or Department that they are students can obtain tickets at half the above rates. The same applies to firms who apply for not less than six tickets for their employees. Prospectuses and tickets are available from the Director of Education, The Polytechnic, Regent Street, London, W.

Conferences for Architects

The Conferences for Architects on Electric Lighting, a very useful feature recently embodied in the programme of the E.L.M.A. Lighting Service Bureau, are extended this year. The conferences opened on January 18th, when, after some opening remarks by Mr. W. F. Moir, Chairman of the E.L.M.A. Council, an address on "Lighting Principles" was delivered by Mr. W. J. Jones. The subsequent programme is as follows:—

Feb. 1—Domestic Lighting, by R. O. Ackerley.
Feb. 15—Lighting of Commercial Buildings, by H. C. Wheat.
Mar. 1—Lighting of Schools, by C. A. Hughes.
Mar. 15—Floodlighting, by H. Lingard.
Mar. 29—Lighting of Theatres and Cinemas, by Waldo Maitland.

On each occasion the discussion is to be opened by a Fellow of the Royal Institute of British Architects. Conferences commence at 7 p.m., and are preceded by light refreshments at 6-15 p.m. We have no doubt that they will serve a most useful end in leading architects to take a keener interest in illumination, and to understand how fine a field for their skill and effort lighting really presents.

National "Safety First" Association

ENQUIRY INTO STREET ACCIDENTS.

Our attention has been drawn to certain statements in the press purporting to forecast the recommendations of the Accident Research Committee of the National "Safety-First" Association. This research into the causes of fatal road accidents covers the period up to December 31st. Returns will still be coming in during the present month, after which they will require tabulation—a process involving several weeks of work—and the Committee naturally cannot proceed to consider any recommendations as to remedies until the tabulation is complete. We are therefore asked to point out that any forecast of their recommendations is without foundation.

Smoke Particles and Condensation Nuclei

Observations of smoke particles and condensation nuclei at Kew Observatory form the subject of a report by Mr. H. L. Wright (Geophysical Memoirs, No. 57). The nature of these nuclei seems to be imperfectly understood. Their variation throughout the year is broadly similar to that of smoke particles, though the contrast between the numbers in summer and winter is less. Easterly winds from London bring smoke particles to Kew in large numbers, and they are also to some degree associated with large numbers of nuceli. The radius of a smoke particle is about ten times as large as that of a nucleus of condensation, and its volume is thus about 1,000 times as great.

TECHNICAL SECTION

COMPRISING

Transactions of The Illuminating Engineering Society and Special Articles

The Illuminating Engineering Society is not, as a body, responsible for the opinions expressed by individual authors or speakers.

A Visit to Watson House

(Proceedings at the Meeting of the Illuminating Engineering Society held, by kind invitation of the Gas Light and Coke Company, at Watson House, Nine Elms Lane, London, on Tuesday, January 10th, 1933.)

BY kind invitation of the Gas Light and Coke Company, a visit to Watson House took place on Tuesday, January 10th. Members and friends assembled for light refreshments at 6-30 p.m., and at 7 p.m. the chair was taken by Lieut-Commander Haydn T. Harrison, M.I.E.E., R.N.V.R. (President).

After the minutes of the last meeting had been taken as read, the Hon. Secretary read out the names of applicants for membership, which were as follows: —

Sustaining Member :—

Chance Bros. & Co. Ltd., Glass Works, Smethwick, Birmingham.

Representative: Dr. W. M. Hampton.

Ordinary Members :—

Swaine, W. .....Director of Research, Institute of Ophthalmic Opticians; Lecturer in Physics and Applied Optics at West Ham Municipal College, 89, Empress Avenue, Ilford, Essex.

Peirce, M. W. .....Illuminating Engineer, General Electric Co. Ltd., Magnet House, Kingsway, W.C.2.

Country Members :—

Ainscow, F. .....Electrical Engineer, 8, Croft Avenue, Simister Lane, Rhodes, Manchester.

Heyes, J. .....Electrical Engineer, 7, Church Walk, Brownhill, Blackburn.

Kjaerulff, Sv. E. .....Electrical Engineer, Staegers Alle 2, Copenhagen (F.), Denmark.

Rudra, N. N. .....Engineer, Calcutta Electric Supply Corporation Ltd., 28, Garden Reach Road, Matisburz, Calcutta, India.

Smith, W. H. .....Electrical Engineer, 55, Broadway, Failsworth, Lancs.

Wadsworth, T. .....Electrical Engineer, Engineering Laboratory, British Thomson-Houston Co. Ltd., Rugby.

The names of those announced at the last meeting of the Society were read again, and these gentlemen were formally declared members of the Society.*

The HON. SECRETARY also mentioned that he had been authorized to make the opportune announcement that the name of the Gas Light and Coke Company would shortly be added to the list of sustaining members of the Society. There were, of course, already a considerable number of members of the staff of the Company who were corporate members. But they would all be glad to hear that the bond between the Company and the Society was to be further strengthened in the manner described. (Applause.)

* *Illum. Eng.*, January, 1933, p. 3.

ADDRESS BY MR. STEPHEN LACEY.

Mr. STEPHEN LACEY, Sales Controller of the Gas Light and Coke Company, then addressed a few words of welcome to the party. In the course of his address he referred to the condition of Sir Francis Goodenough, the immediate Past President of the Society and one of its original members, who, after undergoing a serious operation, was now making good progress towards recovery. Sir Francis had for many years taken a very deep interest in the Society, and he (Mr. Lacey), as his successor in the Gas Light and Coke Company, was very glad to be able to carry on the tradition by welcoming members to this meeting at Watson House.

Mr. Lacey also made a few remarks illustrating the vast scope of the operations of the Gas Light and Coke Company.

Mr. C. A. MASTERMAN then delivered an address descriptive of the work at Watson House. The following is an abstract of the address, which was available in printed form prior to the meeting.

THE WORK OF WATSON HOUSE.

Watson House is one of the main research centres of the gas industry. Here, all problems of gas distribution and utilization are tackled. Other important sides of the Gas Light and Coke Company's work are also carried out at Watson House:

(1) *Chief Stores* depot of the Company.

(2) *Testing Section*, responsible for specifications and quality of goods bought. All fittings, for instance, through which gas passes, are submitted to pressure tests to determine whether there is any porosity or other fault present in the fitting. Over $4\frac{1}{2}$ million malleable iron fittings were tested during the course of last year. One or two samples are taken from deliveries for complete examination, including gauging, metallurgical tests, etc.

(3) *Industrial Section and Workshops*, responsible for developing furnaces and other gas-burning appliances to meet industrial needs. This section keeps in close touch with firms who manufacture such appliances. The workshops also make special fittings and apparatus for out-of-the-ordinary domestic jobs and for the laboratories themselves.

(4) Technical Training of the Gas Sales Department personnel. Apprentices for the Department start their course of training at Watson House. Foremen, fitters and others come here at intervals for refresher courses. Contact is kept with the various technical institutes throughout London, at

which employees of the Company are taking evening classes. There are about 8,000 employees in the Gas Sales Department of the Company, and, clearly, it is impossible for these to come up frequently to Watson House. A monthly technical booklet is therefore issued to keep the district staffs up to-date, while an information bureau is established to help, by telephone, in the solution of difficult district problems.

(5) *Research or Laboratory Section*, with which the visit of the Society of Illuminating Engineers will chiefly be concerned. Having seen the work carried out in the Testing Section, where an apparatus for the determination of light penetration in fog will be inspected, you will first visit the group in the laboratory dealing with fittings and meters.

Demonstrations of distant and local thermostats, plug-in connections, governors and various safety devices are arranged, with some of the new types of gas meters. There is, in the same laboratory, a room-heating section. As a result of prolonged work, methods have been found for the improvement of the thermal efficiency of gas fires combined with a definite improvement in the appearance of these appliances. You will realize that a considerable amount of general research is in progress on comfort conditions, as they relate to artificial methods of heating.

New appliances are sent by their makers to Watson House for test. No apparatus is put on the list of the Gas Light and Coke Company unless the results of such tests are entirely satisfactory. The tests deal with general construction, thermal efficiency, facilities for maintenance, and, finally, combustion standards.

In the Chemical Laboratory you will see standard methods of analysis and work which is in progress on the protection of underground pipes from corrosion and on the influence of gas quality on corrosion inside gas appliances.

In the Gas Laboratory, flue-gas analyses are carried out to an accuracy approaching two parts per million, and here there is also a recording carbon monoxide apparatus, which is the first one to be installed in this country. A recording calorimeter and other control apparatus are in operation in the same room.

In the Photometric Laboratory is an N.P.L. pattern photometer with a large mirror device for determining the distribution of light from any unit. Several types of portable photometer are also available for the testing of street-lighting installations, etc.

The work here includes the examination of lighting units or lighting equipment submitted to the Company by makers, and the development of special units for special purposes. For instance, the flood-lighting units used at the International Illumination Congress demonstrations last year were developed entirely in this laboratory. Standard tests include polar curves or, with asymmetric distribution, iso-candle diagrams. Construction and maintenance details of the lighting units are also taken into account. Designs for complete lighting installations are dealt with, these being for street-lighting purposes, or more special items such as advertising signs, shop-window displays, etc.

All lighting units and equipment bought by the Company are examined in relation to specifications, most of which are prepared in the department. In connection, for instance, with mantles there are a number of tests for lighting efficiency, and also for strength against shock, ageing, etc. The gauging of mantle and ring in relation to the type of fabric and impregnation is an important feature.

There is, further, much research in progress, and it has to be remembered that the closest attention to detail is required if gas lighting is to be a success. It is realised that, in the past, gas lighting has not been wholly satisfactory in certain connections where in fact it can give entirely satisfactory service, and every attempt is being made to maintain correct gas-air ratio, correct dimensions, pre-heating and so forth, so that a reliable and adequate light is maintained without trouble to the consumer.

The problem of blackening of ceilings above lighting burners is being examined.

Switch control has been introduced, and methods for reinforcing the structure of mantles are undergoing review. Meanwhile, automatic ignition of lighting burners is being intensively considered, this being a matter in which success would be attended with very considerable consequences, not only in the lighting field but also for other uses of gas.

A new lighting unit will be on view in which the heat output is so controlled as to lead to sufficient radiant heat being kept up in the winter to give adequate heating without the need for any other heating system in a factory, supposing a 10 foot-candle illumination is provided. The special heating arrangement can be eliminated in the summer.

In the Cooker Laboratory will be seen modern gas cookers which have recently been developed, and other novel cooking apparatus. There is a small artificial room in which the effect of highly vitiated air upon the combustion of various appliances is determined. The results so far show that a degree of air vitiation far beyond any practical limit can be produced without deleterious effect upon the combustion of the gas.

In the Hot Water Laboratory there will be seen various water heaters, not only of the normal geyser type but automatic distributing geysers, storage water heaters—on both large and small scale—and also central heating and steam boilers. One of the hot-water laboratories is automatically controlled, so far as temperature is concerned, so that comparable results may be obtained in testing out storage water heaters, wash boilers and the like. Here there will be arranged a demonstration of the apparatus used in a recent enquiry into the factors controlling ventilation and of certain modern flue fittings, developed as a result of this investigation.

Votes of Thanks.

After the address, reproduced above, had been presented in abstract by Mr. Masterman, a film was shown illustrating the complete process of equipping and testing a gas lamp before it was considered fit to be sent out.

The President, in rising to propose a vote of thanks, recalled the long association of the Gas Light and Coke Company and Sir Francis Goodenough (Mr. Lacey's predecessor) with the Illuminating Engineering Society. They had learned with great satisfaction that Sir Francis was making good progress, and he asked Mr. Lacey to convey to him their sincere wishes for a speedy and complete recovery. (Applause.) He felt sure they would all appreciate Mr. Lacey's presence, and the kind manner in which he had made them welcome. He wished also to propose a cordial vote of thanks to Mr. Masterman for his address—he had prepared an admirable summary of what they were about to see—and to the Gas Light and Coke Company for their hospitality. (Applause.)

The visitors then broke up into six parties, who were conducted on a tour of inspection of the laboratories.

The Theory and Specification of Opal Diffusing Glasses

(Communication from the Staff of the Research Laboratories of The General Electric Company, Ltd., Wembley, England.)

(Paper read at the Joint Meeting of the Illuminating Engineering Society and the Society of Glass Technology, held at Caxton Hall, Caxton Street, London, S.W.1, at 6-30 p.m., on Tuesday, December 13th, 1932.)

SUMMARY

In Part I of the paper the Authors' theory of the diffusion of light by turbid media is presented in a simple form which can readily be applied to practical work in connection with opal glasses.

In Part II, the three fundamental glass constants μ, q and NB are discussed fully and a description is given of methods for measuring the photometric quantities from which the constants can easily be determined. It is then shown how a figure of merit, assessing the relative suitability of different opal glasses, may be obtained. Finally, a method of specifying the intrinsic efficiency of opal glassware to be used in lighting fittings is outlined.

(Part I)

By J. W. RYDE and B. S. COOPER

(1) Introduction.

THERE are two ways in which glasses may be made to diffuse the light falling upon them. In the first place, surface irregularities may be produced by etching or grinding an initially clear sheet of glass, and, secondly, diffusing material can be formed in the body of the glass by introducing certain compounds into the batch mixture. In the latter case the glass is generally spoken of as "pot opal." Combinations of the two methods are also frequently employed; thus opal glasses containing more or less uniformly disseminated particles may, in addition, be given an etched surface finish. On the other hand, clear glass is often provided with a thin layer of a dense opal glass on one of its surfaces. This form is generally known as "flashed opal" if the coating is very thin, and "cased opal" if the clear and opal layers are of the same order of thickness.

It is now fairly well known that the particles producing the diffusion of the light in opal glasses are quite transparent in themselves. In the same way, cloud or a thick mist may strongly diffuse the light falling on it, although the individual water droplets are clear. The diffusion is, in fact, due to repeated diffraction and reflection of the light by the particles, and this in turn is dependent on there being a difference between the refractive indices of the particles and of the material containing them.

In most opal glasses the particles are generally very much smaller than the droplets which normally occur in clouds or fogs. They are also much more numerous; thus, up to a million million of them may occur in a single cubic centimetre of an opal glass. In the case of the more common "fluoride" opals the particles separate out on cooling, and have been shown[1]* to be composed of sodium and calcium fluorides. Fig. 1 shows a photomicrograph of a pot-opal glass taken with a magnification of 5,000.

FIG. 1.—Photomicrograph of Opal Glass with dark ground illumination. (Magnification: 5,000.)

This was taken with dark ground illumination, and shows the transparent nature of the particles particularly well.

(2) Critical Survey of Attempts to Formulate a General Theory.

Many attempts have been made from time to time by various workers to build up the fundamental theory of the diffusion of light by small particles. It would, however, take far too long to give a complete historical sketch of the work done in this very extensive field. Here we shall give a critical survey dealing chiefly with those parts of the general problem which are more or less directly applicable to opal glasses. The problem naturally divides itself into two parts; the first concerns the way in which light is scattered by a single particle, and the second deals with the resultant effect of a collection of great numbers of the particles when they are distributed at random throughout some medium.

At the end of the last century, the late Lord Rayleigh, in a well-known series of papers, dealt with the way in which light is scattered by a very small particle. He showed, among other things, that the amount of light scattered varies inversely as the fourth power of the wavelength, and thus explained the blue colour of the sky as being due to molecular scattering. He was largely concerned with particles whose size was far smaller than those we meet with in opal glasses, so that this pioneer work cannot be applied to our present problem.

In 1908 Gustav Mie[2] published a classical paper dealing with the scattering of light by spherical particles not restricted in size. The results were extremely complicated, and for every different case very lengthy computations were needed to obtain a numerical result. He showed, however, that as the diameter of the particles was decreased the results became simpler, and finally reduced to Rayleigh's results in the limiting case.

In 1914 Rayleigh,[3] in another paper, which is not nearly so well known as his earlier series, gave a simpler theory applicable to any particle diameter, provided that the relative refractive index of the particles and the suspending medium is not far from unity.

Now as regards the resultant effect of a collection of particles, the first step was made in 1905 by Schuster,[4] who first introduced the conception of two diffuse fluxes of light travelling through the medium in opposite directions. Although a certain complication was introduced by the assumption that the particles themselves were emitting light, the case treated was fundamentally almost the simplest possible. The particles were supposed to be so minute that, as was shown by Rayleigh for this case, as much light is scattered in the backward as in the forward direction by each particle. The light incident on the outer layer of

* All references are given in the bibliography at the end of Part II.

particles was also assumed to be completely diffused initially. Finally, any boundary effects due to the medium in which the particles might be suspended were not considered. These assumptions were legitimate for the particular astrophysical case with which he was concerned, but they are by no means allowable in the opal glass problem.

In 1918 Channon, Renwick and Storr[5] developed a theory intended to give the analytical expression for the variation of the transmission and reflection factors of a sheet of opal glass as the thickness is changed. They did not attempt to consider the particles themselves in any way, but they virtually made the same assumptions as Schuster. Their results naturally were effectively the same as his, but they made the mistake of thinking that they would be generally applicable to opal glasses. This is not so, because their method of derivation neglected the boundary reflections and, in particular, the important effect produced by total internal reflection at the glass-air interfaces. Apart from this, their method is sound, but it only refers to the simple case when the incident light is diffuse.

Silberstein,[6] in 1927, was the first to attempt the treatment of the more difficult case for incident parallel or collimated light. He introduced a factor, to be determined by experiment, which would allow for the fact that more light is scattered by a particle in the forward than in the backward direction, except for infinitesimal particles when the two quantities become equal. His work was, however, entirely vitiated by the fact that he wrongly assumed that the ratio of the amounts scattered by a particle in the forward and backward directions is the same for both the diffuse flux and the residual collimated beam existing inside the glass. This mistake had the result of making his expressions really equivalent to the case for diffuse incident light which had already been dealt with by previous authors. He also made no allowance for boundary effects.

Gurevic,[7] in 1930, gave a treatment of the problem restricted to scattering particles in air and to the case of diffuse incident light. He attempted a method of classification based on his expressions, but this is quite inadequate for the opal glass problem, as he does not consider the amount of unscattered light transmitted (which, as we shall see, determines whether or no the light-source is obscured by the glass), and again no allowance was made for the reflection effects at the surfaces.

Dreosti,[8] in 1931, gave a theory which covered the cases of both diffuse and collimated incident light, and proceeded to apply it to opal glasses. He, however, made the serious mistake of neglecting the effects of surface reflections. He and others appear to have thought that the only surface reflection effect necessary to consider was that due to external reflection. As a matter of fact, the coefficient of reflection of the outer air-glass interface is about 0.04 for parallel and 0.09 for diffuse incident light[10]; these are thus not large. On the other hand, we have found that of the internal diffuse flux arriving at the glass-air surface only about 60 per cent. emerges directly; the remainder is totally reflected and has to undergo further diffusion and absorption before reaching the other surface, where the same thing happens again. It will thus be seen that the effect of the total internal reflection is by no means negligible, and that it indeed considerably modifies the predicted values of the proportions of the incident light which ultimately emerge as the transmitted and reflected fractions.

In all the developments of the theory described above, the final expressions did not allow the effects of given changes in the size or nature of the particles to be calculated. What was always done was to introduce at the start certain constants or coefficients which were unknown functions of the diameter and constitution of the particles. The only exception to this is the special case when the diameter is indefinitely small, but then, as already mentioned, the results are not applicable to the opal glass problem. These constants, or combinations of them, appeared in the final results as symbols whose values had to be determined experimentally for every case.

In 1931 Ryde and Cooper,[9, 10] published a comprehensive theory in which, for the first time, due allowance was made for all the boundary reflection effects, and the necessary constants referred to above were determined in terms of the wavelength of the light, the diameter of the particle and the refractive indices of both particle and medium. In the preliminary work attempts were made to utilize the very general, but extremely complicated, theory of Mie for this purpose. Later it was realized that the Rayleigh theory of 1914 would be quite sufficiently general for all opal glass problems. Even with this simpler basis, however, the development of the expressions for the constants was by no means easy. In order to make the resulting expressions readily applicable in practice, all the functions entailing lengthy computations were worked out numerically and tabulated.

Having found the constants in terms of the fundamental data for the particles, the next step was to determine the transmission and reflection coefficients for a collection of the particles in air. This was done for both diffuse and collimated incident light. Allowance was made in the latter case for the fact that the quantity of light scattered in the forward and the backward directions is different for the collimated and diffuse portions of the flux existing inside the layer. Lastly, the complicated effects produced by the total internal reflection were investigated, and the general theory, including all the boundary reflections, was developed so as to be applicable to particles suspended in any medium.

Since the theory had been developed in terms of the properties of the particles themselves, it was possible to invert the process, and then, as a check, to calculate the diameter and number of particles present from measurements on the transmission and reflection of a sheet of the opal glass containing them. This was done, and good agreement was found between the calculated values and those determined by direct counts and measurement from photomicrographs.[10] Similar tests with suspensions of quite different particles in liquids were also made.[11] These are extremely severe checks of the theory, as will be realized the more if all the varied steps in its development are reviewed. Numerous other tests of the theory will be found in the last papers cited.

Since all previous theories had not included the effects of the internal boundary reflections, it may naturally be asked, why was there not some discrepancy observed when any experimental checks of them were made? The reason is that none of these theories was based on the fundamental data for the particles, so that no searching checks could, in fact, be carried out. The very fact that the values of the constants had to be determined experimentally meant that errors due to neglect of the boundary reflection effects, etc., would be thrown on the constants; these erroneous values were always accepted without question, since there was no really adequate way of testing them. Again, if the faulty values were used to calculate, for example, the transmission of a sheet at some new thickness, the errors would cancel out, provided that the new condition was not too far from the old. When, with bigger changes, discrepancies did appear, the natural explanation would be that the material was not strictly uniform.

The new theory forms a broad basis upon which numerous practical problems concerning opal glassware can be built up. Some of these have already been published. In particular, the theory of the transmission of spherical globes surrounding the light-source has been worked out in detail.[10, 11]

(3) Uses of the Theory.

When light is incident on a sheet of glass containing large numbers of scattering particles, some is transmitted, some reflected, and the remainder absorbed. On the other hand, if an opal fitting completely encloses the light-source, a certain fraction of the light is transmitted and the rest is absorbed, partly in the glass and partly in the canopy closing the aperture.

It will, of course, be realized that without any theory to go on, the measurement of these transmission or reflection factors would really tell us very little. Thus we should not know what the values would be if the sheet or globe were made up of a different thickness, nor could the transmission factor or efficiency of a globe be estimated from measurements upon a small sample of the glass. Again, the effect of changing the type of canopy used could not be predicted and, if it should happen that a given sample of glass proved to be unsatisfactory, it would not in general be possible to assign the reason.

The object of the present paper is to present the results of the theory in a convenient graphical form and to show how it may then be readily applied to various questions such as these. We shall then go on to show how the intrinsic merit of different glasses, to be used in fittings, can be assessed, and to illustrate a simple method of specification. Before dealing with these problems in detail we shall devote a little time to the consideration of some rather more general questions.

(4) General Considerations.

It may be said that calculations such as described in the last section would not be worth while, for the following reasons. First of all, opal glasses are not strictly homogeneous throughout their thickness, nor indeed in different parts of the same globe or sheet. Secondly, glass from the same pot, when blown in different shapes, such as flat sheets, large or small globes, etc., does not always have quite the same properties in each case. This effect is due to the different rates of cooling which entail differences in the particle size and number.

All this is perfectly true, but it is our contention that these changes, provided that their existence is realized, do not detract from the usefulness of the above types of calculation. These considerations are nevertheless important, and, even at the risk of appearing to labour the point unduly, we shall go into them in more detail.

As regards the first point, if, for example, we consider the efficiency of a globe, the variations in different parts of it will average out, unless indeed it is of very poor manufacture. Again, the variations throughout the thickness mainly occur in a thin skin on the surfaces. In practice, therefore, the calculated results will be found to agree quite sufficiently well with those observed. Of course, when accurate tests of the theory are being carried out, the surface skin should be removed. Knowing, however, that variations may occur to a certain extent, one naturally takes the precaution of measuring more than one small sample of any new glass when it is desired to determine its constants. Some idea of the probable accuracy of any prediction based on the mean constants may then obviously be judged from the degree of variation found in the values of the constants obtained from the different samples.

The second point, that glass from the same pot has somewhat different optical properties when made up into different forms, or even similar shapes of different thicknesses, is easily understood. We have seen that with different rates of cooling the particle size and number may differ and so alter the glass constants. Thus, although the manufacturer would say that the different types of article were made from the same glass, it would really be more accurate to consider them as composed of different opal glasses. We have found, however, that the changes in the constants corresponding to alterations in thickness are very small, provided that the thickness exceeds a certain value. Fortunately, this value turns out to be thinner than is employed in opal glassware. It is unlikely, therefore, that this effect will produce any large variations in practice. Hence calculations based on glass from one form of article will generally allow at least a fair estimate to be made of the optical properties of some other form when made from the same glass.

Lastly, it may be said that different consignments of glass may differ somewhat from one another, so that the constants will change. The amount of any such variation depends, of course, on the care exercised by the manufacturer. Until recently there has been no sound method of determining the intrinsic optical qualities of opal glasses, but now that the basic theory has been developed, its use cannot be criticized on the grounds that the product may not be accurately uniform It is, in fact, one of the objects of the theory to enable any changes in the intrinsic quality of the glasses to be followed, and to indicate the general lines on which an improvement in the optical properties of an opal glass, intended to be used for any particular purpose, may be effected.

The first practical problems to which we shall now give attention are those concerned with the visibility of the light-source.

(5) The Visibility of the Light-Source.

In general, the object of an opal globe is to diffuse the light from the source. In some cases, however, the diffusion is incomplete, and then the source remains faintly visible. In particular, when an electric lamp is used, and the opal does not diffuse the light sufficiently, the filament can be seen through the globe as a sharply defined thin orange or red line. The reason that it appears coloured is that the particles in the glass scatter blue light more than red, and hence a greater proportion of red rays gets through the glass without undergoing diffusion.

In a certain class of glassware, sometimes known as opalescent, this effect is deliberately produced by restricting the scattering power. The particles produced in this glass are generally much smaller than in opal glasses, and, although they may be present in larger number, their diffusing power is considerably reduced owing to their small size. With globes of this type the source appears of a bright orange colour, while the rest of the globe is seen to be bluish.

On the other hand, in the case of opal glass globes, it is important that the source should not be visible, since otherwise it will detract from the general appearance of the fitting.

Now, even the opalescent types of glass would obscure the light-source if they were made sufficiently thick, while, on the other hand, it can always be seen through opal glasses if they are made thin enough. In other words, what really matters is the amount of diffusing material present between the source and the eye. Since it is impracticable to make globes either very thick or extremely thin, the main factor in practice is the intrinsic scattering power of the glass.

The first problem which immediately arises is, how is the scattering power to be defined, and the second is, assuming that this be known for a given glass, what will be the wall thickness of a globe which will only just completely obscure the source? A knowledge of this latter thickness is very important. It is, in fact, obvious that if we use a greater thickness than this, the appearance of the globe will not be improved, and yet its absorption will be greater than necessary.

We shall use the symbol q for the total scattering coefficient of a glass and X for its thickness. The ratio β of the brightness of the source, measured through the globe, to its actual brightness is given closely by the following expression, if the superimposed field brightness is left out of account.

$$\beta = (1 - r_o)^2 e^{-qX} \qquad (1)$$

Here r_o is the coefficient of surface reflection of the glass, and may for practical purposes be taken as 0.04. It will thus be seen that we can always find the value of q for a given glass by measuring β for a sufficiently thin specimen and then applying equation (1). The details of the measurement will be discussed fully in Part II, here we need only note that, as already mentioned, the proportion of the light scattered, and therefore q, depends upon the wavelength of the light used. For practical purposes we shall assume that q is always measured for an effective wavelength given by the peak of a curve representing the product of the wavelength distribution of the source and the normal luminosity curve for the eye. For gasfilled lamps this effective wavelength may be taken as 5.7×10^{-5} cms.

Now, as regards the second problem, knowing q, how are we to calculate the minimum globe wall thickness X_v that is necessary to obscure completely the source of light within the fitting?

Let c be the candle-power of the light-source, d be the diameter of the globe, and η the fraction of the light from the source which is transmitted by it. Then if $(qX)_v$ is the value of qX when the source is just not perceptible through the globe, we have shown[12] that

$$e^{-(qX)_v} = \phi \frac{\eta}{d^2} \frac{4c}{\pi b (1 - r_o)^2} \qquad (2)$$

where ϕ is the Fechner fraction and b is the actual surface brightness of the light-source.

From the form of (2) it will be seen that $(qX)_v$ is practically independent of the kind of opal glass employed, because the effect of small changes in η on $(qX)_v$ is slight.

In the case of incandescent-filament lamp sources it can be shown that, if the diameter of the globe and its wall thickness X are measured in centimetres, equation (2) can be written in the simple form—

$$(qX)_v = 2.3 \left(\log_{10} \frac{d^2}{W} \right) + p \qquad (3)$$

where W is the wattage of the lamp used. With gasfilled lamps the value of p may be taken as 11.0 for all lamp ratings between about 40 and 1,000 watts.

As a matter of interest, the complete expression for p is given by

$$p = 2.3 \log_{10} \frac{\pi^2 b (1 - r_o)^2}{\eta \epsilon k \phi} \qquad (4)$$

where ϵ is the efficiency of the lamp in lumens per watt and k is a correction factor to allow for the fact that, although we have measured q for the effective wavelength of the source, it should really refer to the effective wavelength of the emergent unscattered light, which is redder. It should also be noted that, strictly speaking, ϕ depends upon the distance of the eye from the globe; here we have assumed this to be only a few feet, but the change with distance is not large. By experiment we have found that the product $k\phi$ may be taken to be 0.01 if the distance is two feet, and if q is determined for the effective wavelength of 5.7×10^{-5} cms.

Returning to the problem proposed, we now see that, having measured q for a given glass, then for a lamp of given wattage we can immediately determine $(qX)_v$, by means of equation (3), for any desired diameter of globe. The minimum wall thickness X_v which will just obscure the source is then found by dividing $(qX)_v$ by the known value of q. Any greater wall thickness than this will, of course, be inefficient. Naturally, owing to variations in thickness between different fittings and in different parts of the same fitting, a manufacturer must apply a safety factor to the theoretical value of X_v, since this assumes strict uniformity.

The converse problem is also important. Given the lamp rating, the globe diameter and the wall thickness, we can find the value of the scattering coefficient q which must be equalled or exceeded by all glasses which are to obscure the source in the given circumstances. If q is measured for a number of glasses it is thus possible to reject certain of them immediately as being unsuitable for fittings of given dimensions used with specified lamps.

Strictly, the value of $(qX)_v$ derived from the above equation refers to spherical globes. It has been found, however, that the equation is applicable to fittings of quite different shapes (provided they are not very extreme) if the value of d is taken to be that of a sphere having about the same surface area as the fitting in question. It is often convenient to take d to be twice the greatest distance from the approximate centre of the globe to any part of the wall liable to be seen when the fitting is installed. This will then ensure that the source will not be visible under practical conditions of use.

In order to illustrate how accurately the thickness X_v can be calculated by the above equation, a few comparisons of observed and calculated values are given in Table I. The observed values were obtained as follows: A point on an actual fitting was chosen such that its distance from the filament of the lamp was equal to the radius of a sphere having the same surface area as the fitting. The glass at this point was ground down in stages, and repolished, until the filament just became visible. To save repolishing the ground surface at frequent intervals, a thin glass cover slip placed over a few drops of xylene (refractive index 1.50) on the ground surface gave the effect of polish whenever it was required to make an observation. When the thickness was reached at which the lamp filament was just distinguishable, the glass was finally repolished. The thin portion was then cut out and its thickness measured. As will be seen from the table, this value was in good agreement with that calculated.

TABLE I

	q	$(qX)_v$ by eqn. (3)	X_v calc. (cms.)	X_v obs. (cms.)
Large fitting. Type A ..	110	12·8	0·116	0·12
Large fitting. Type B ..	130	12·8	0·098	0·09
Opal lamp bulb	230	10·9	0·047	0·05

(6) The Transmission and Reflection Factors of Sheets and the Transmission Factor of Complete Globes.

The theoretical work shows that those optical properties of opal glasses which concern us here may all be expressed in terms of the following constants, which are intrinsic to the particular glass:

(1) n_o, the refractive index of the glass.

(2) q, the total scattering coefficient. This is a function of the number, size and composition of the particles.

(3) NB, a constant composed of the product of N, the number of particles per unit volume, and B, a special scattering coefficient depending on their diameter and the composition. In what follows we shall, in general, treat this product as one constant.

(4) μ, a combined absorption coefficient relating to the glass and the particles.

Now the first constant n_0 does not vary to any great extent for different opal glasses, and may, for our present purpose, be taken to have the value 1.5. The uses of the second constant q have already been fully discussed in the previous section, so that it now only remains to deal with μ and NB.

In the present paper we shall be more concerned with the relationship between these and the photometric properties of the glass than with their intimate connection with the particles themselves. In the cases where the latter is important, the relationship will be explained in more or less general terms. It would take far too long to deal adequately here with this other side of the question, but, if desired, reference can be made to the original papers[9, 10] for the theoretical aspects.

Just as a knowledge of the constant q enables us to calculate the minimum wall thickness necessary to obscure the light-source, so the knowledge of μ and NB allows us to calculate the following photometric factors for any given thickness of glass.

(*a*) The total transmission factor τ' and reflection factor ρ' of an opal sheet, when the incident light is in the form of a parallel or nearly parallel beam.

(*b*) The corresponding total transmission τ and reflection ρ when the incident light is diffuse.

(*c*) The transmission factor σ of an ideal spherical globe of uniform thickness, which completely surrounds the light-source placed at its centre.

From these it is then possible to proceed directly to the solution of practical problems. Thus, to calculate the actual light output ratio of a fitting, we first find σ and then apply corrections to allow for the fact that the aperture is covered with a canopy. But, first of all, we must consider how the constants μ and NB can be determined.

If measurements of the values of a suitable pair of the factors given in (*a*) to (*c*) above are known, these constants can be found. Of the many pairs which might be chosen, we have found τ' and ρ' to be the most convenient. It will be remembered that these refer to the case when the incident light is parallel. We shall defer a description of the apparatus used and the actual method of measurement until Part II. Here it will be assumed that the values of τ' and ρ' have been determined photometrically from a sample of glass of thickness X. The measurements may be made on a plane specimen or on a fairly flat piece cut from a fitting.

The expressions representing the rigid analytical relations between the measured photometric factors and the constants are very complicated. This is so much the case as seriously to hinder their general application, in the original form, to practical work. However, by making certain simplifying assumptions, which are entirely justified so long as we are dealing with opal glasses, it has been found possible to present these relations in the form of simple curves. One set of such curves, connecting τ and ρ with the constants, has already been published,[11] but a new set referring to the more easily measured pair τ' and ρ' will be given here.

The simplifications and approximations employed in the construction of the new curves are as follows: In the first place, as already mentioned, we shall assume that the refractive index of the glass is 1.5. Secondly, it will be assumed that the absorption coefficient μ is small compared with the scattering coefficient q; this is always the case with opal glasses. Thirdly, it will be supposed that the glass is not so thin, or the scattering power so small, that the proportion of unscattered light emerging is large. This is really no restriction in practice, because no appreciable errors will appear unless so much light emerges without diffusion that the source would be seen very strongly through the glass. Lastly, we shall assume that the ratio τ'/τ is equal to 1.10. The theory indicates that the value of this ratio will always lie between the limits 1.06 and 1.18, and, in practice, it is found generally to be round about 1.10. Various checks we have made show that the likely deviations from this value will not seriously affect the results.

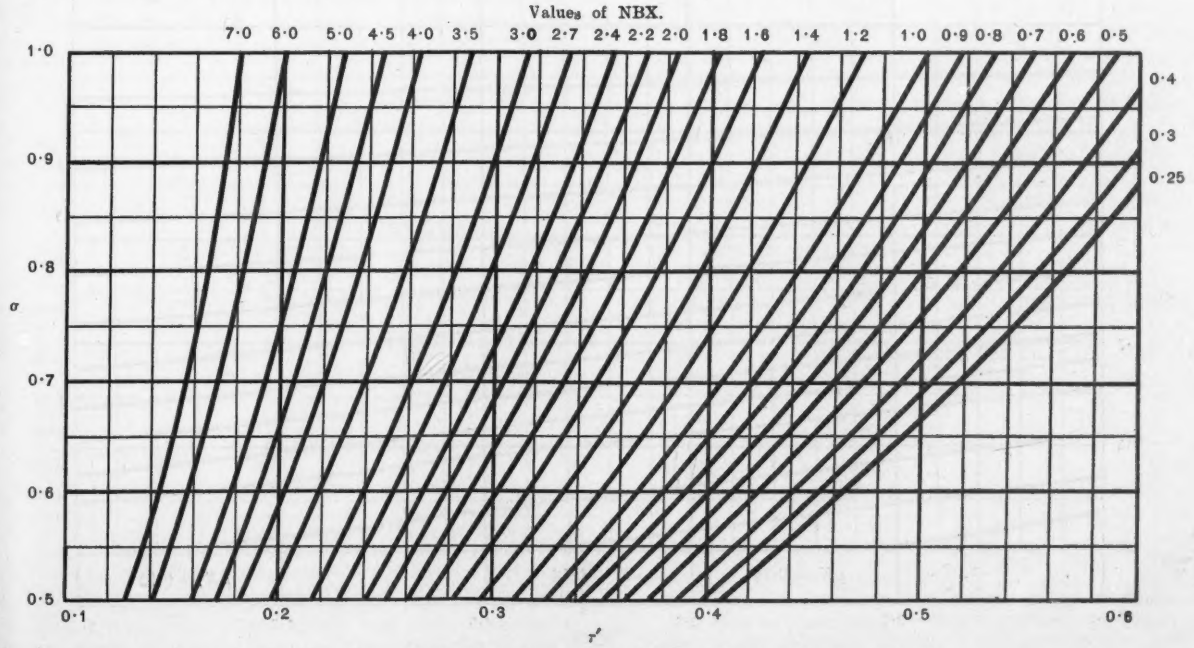


FIG. 2.—Curves of NBX in Terms of σ and τ'. (Note that $\sigma = \tau'/(1-\rho')$

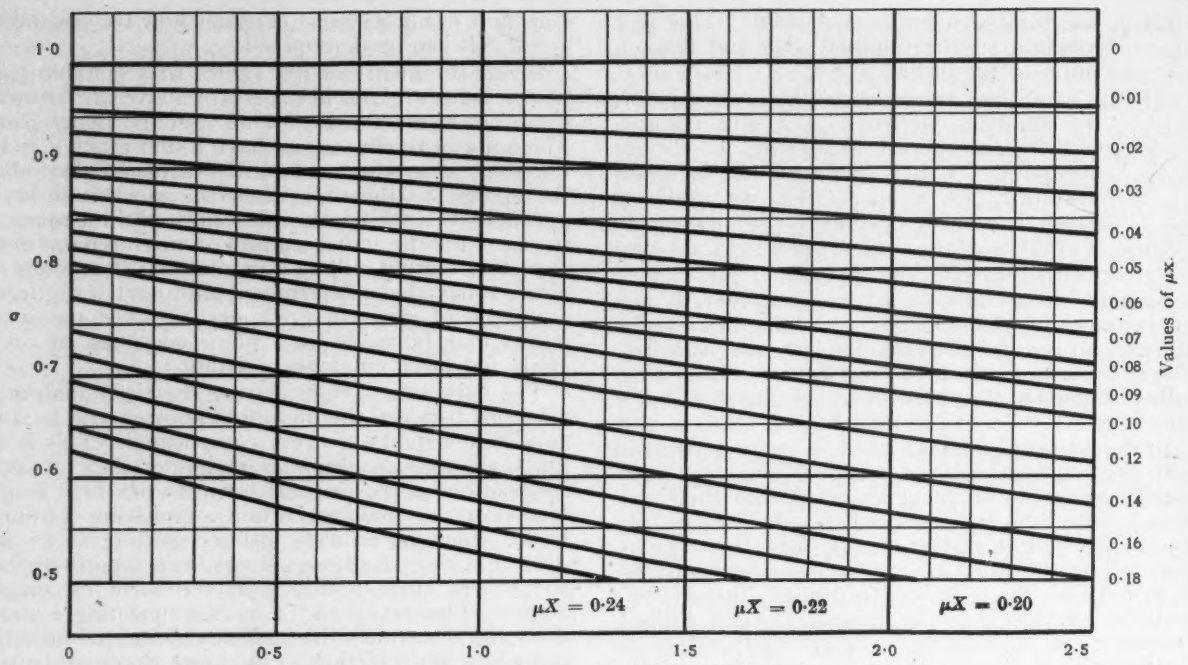


FIG. 3a.—Curves of μx in terms of σ and NBX. (Note that $\sigma = \tau'/(1-\rho')$.

These assumptions greatly simplify the problem and are quite legitimate, except when great accuracy is required. They can be shown to allow the analytical expressions to be represented in a variety of ways, but the following scheme has been found to be the most convenient.

Two families of curves are constructed as shown in Figs. 2, 3*a* and 3*b*. The first is chosen to represent the relation between σ and τ' for various values of the product NBX, while the second connects σ and NBX for various values of the product μX.

Now, by reason of the following important relation[10]

$$\sigma = \frac{\tau'}{1-\rho'} \qquad (5)$$

the curves can be immediately used if τ' and ρ' have been measured. On the other hand, they also give directly the value of σ, if NBX and μX are given. The latter case is of frequent use, as we shall see later.

It is important to realize that due allowance for the boundary reflections, both external and internal, has been made in constructing these curves. They therefore apply without any further correction.

It should also be noted that the curves strictly apply only to pot opal glasses. In general, however, reasonably good results will be obtained in the case of flashed or cased opal glasses, provided that the thickness X is taken to refer to the opal glass portion.

We shall now work out a series of examples to illustrate how the curves can be used to solve a number of different problems.

EXAMPLE 1.

The determination of the constants μ *and* NB *from measured values of* τ' *and* ρ'.

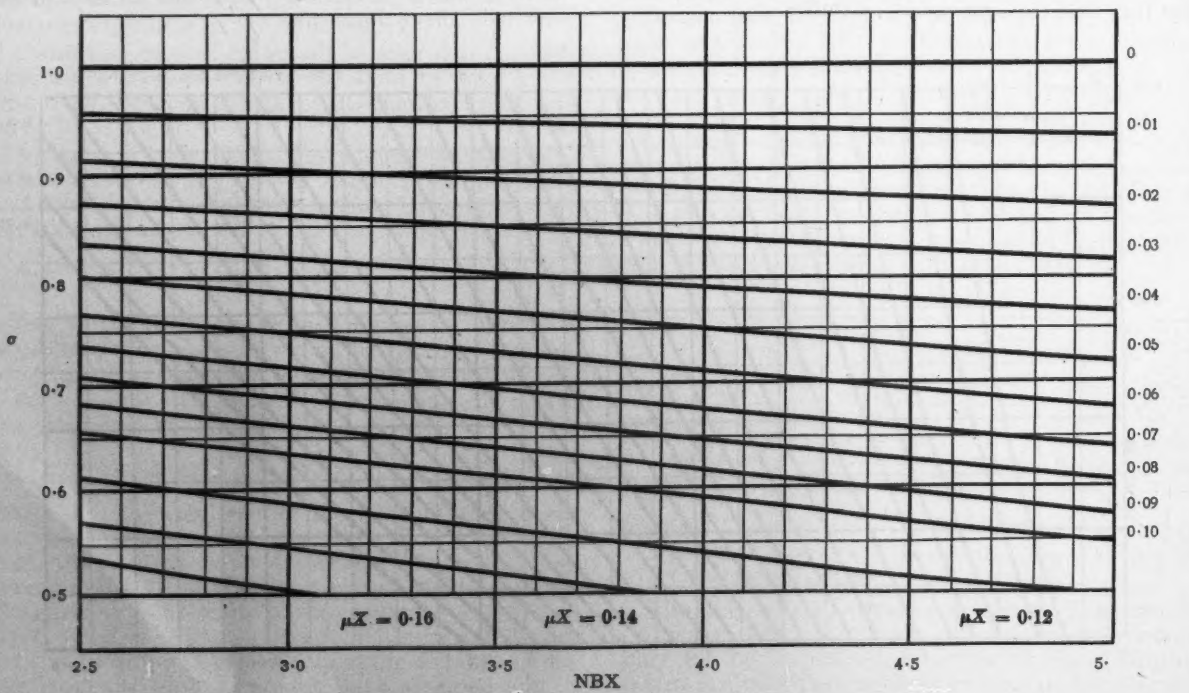


FIG. 3b.—Curves of μx in terms of σ and NBX. (Note that $\sigma = \tau'/(1-\rho')$.

Suppose the measured values for a certain specimen of the glass, having a thickness X to be:—

$$\tau' = 0{\cdot}535 \qquad \rho' = 0{\cdot}426 \text{ when } X = 0{\cdot}127 \text{ cms.}$$

Applying equation (5) we obtain $\sigma = 0.935$, and from the values of σ and $'$ we see that from Fig. 2 the product NBX = 0.67.

Then knowing the values of σ and NBX, we find from Fig. 3 that $\mu X = 0.023$.

Since we know X, the values of the two constants follow immediately. Thus—

$$\mu = 0{\cdot}18$$
$$NB = 5{\cdot}3$$

It will be seen that a similar procedure can be used if any two of the three quantities τ', ρ' and σ are given, for a known thickness of glass.

Once the constants have been found, the various optical properties of the glass can be determined for any given thickness. How this may readily be done is illustrated in the following examples.

EXAMPLE 2.

Knowing τ' and ρ' for one thickness, to estimate their values corresponding to any other thickness.

Let us use the same data as in the first example. Thus, suppose we are given $\tau' = 0.535$, $\rho' = 0.426$ when X = 0.127 cms.

By Example 1 we have seen that the glass constants are NB = 5.3 and $\mu = 0.18$.

Suppose now that we require the values of τ' and ρ' corresponding to some new thickness X_1, which we will take as 0.09 cms.

Now

$$NBX_1 = 5{\cdot}3 \times 0{\cdot}09 = 0{\cdot}48$$
$$\mu X_1 = 0{\cdot}18 \times 0{\cdot}09 = 0{\cdot}016$$

Then from Fig. 3, using NBX_1 and μX_1, we find $\sigma = 0.955$, and from Fig. 2, using NBX_1 and σ, we find $\tau' = 0.578$. But from equation (5)

$$\rho' = 1 - \frac{\tau'}{\sigma}$$

so that knowing τ' and σ, we find $\rho' = 0.395$. Hence the required results are

$$\tau' = 0{\cdot}578$$
$$\rho' = 0{\cdot}395$$

In order to show how well the calculated results agree with observation, values of τ' and ρ' were calculated for a number of thicknesses of a certain glass and curves plotted. There are shown in Fig. 4, in which the circles represent experimental values,

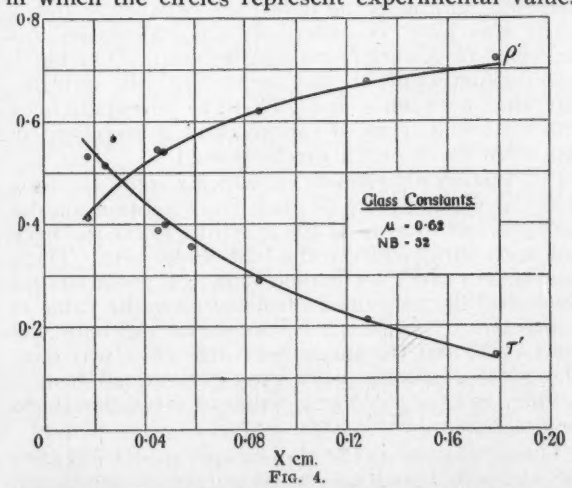


FIG. 4.

obtained by grinding down the specimen to different thicknesses and repolishing each time. The constants for the glass used in this test, as determined from Figs. 2 and 3, were NB = 32.0 and $\mu = 0.62$. It will be seen that the agreement is satisfactory.*

EXAMPLE 3.

Having measured τ' and ρ' for one thickness, to determine the transmission factor σ of a complete globe made of the same glass, but of some other thickness.

Let the values measured for the specimen be

$$\tau' = 0{\cdot}38 \qquad \rho' = 0{\cdot}54 \text{ when } X = 0{\cdot}20 \text{ cms.}$$

By using the method of Example 1 we find that the values of the glass constants are

$$NB = 8{\cdot}2 \text{ and } \mu = 0{\cdot}25$$

Suppose we wish to find the transmission of a spherical globe having a wall thickness $X_1 = 0.25$ cms. We have

$$NBX_1 = 2{\cdot}05 \text{ and } \mu X_1 = 0{\cdot}063$$

From Fig. 3 we obtain $\sigma = 0.78$. Thus the light-output ratio of a spherical globe of the given wall thickness, completely surrounding the light-source, would be 78 per cent, if made of the same glass as the specimen.

In the next section we shall see how this figure is to be corrected so as to allow for the effects of the canopy, etc.

(7) THE LIGHT-OUTPUT RATIO OF FITTINGS.

The light-output ratio of an actual fitting depends not only on the quality of the opal glass globe, but also on many other factors, such as the reflection factor and shape of the canopy. When, therefore, we are interested in the performance of the glassware itself, some standard method of measuring the light-output ratio of the globes is needed. It is desirable that the conditions laid down for this should not differ seriously from the state of affairs obtaining in practice. At the same time, they should be such that the theoretical treatment of the case is not too involved.

A simple method of meeting both requirements is as follows. An uncapped electric lamp is used as the light-source, and it is suspended inside the globe by means of fine wires. The position of the lamp is to be that normally occupied by the light-source when the fitting is in use. In this way, the absorption effects due to the lampholder and support, which may vary in different fittings, are eliminated. To overcome the larger variations produced by different types of canopy, the aperture is closed by a flat plate or card. The side of the card facing the interior of the globe is to have a known reflection factor r, while the other side is to be whitened with the same material as is used to cover the inside surface of the photometric integrator.

We shall, in what follows, use the symbol η_0 for the light-output ratio of a globe measured under the above standard conditions.

It may be shown theoretically that the ratio of η_0 to σ is given closely by

$$\frac{\eta_0}{\sigma} = \frac{1 - \rho'}{(r - \rho') + a(1 - r)} \qquad (6)$$

in which

$$a = \sec^2 \frac{\theta}{4}$$

and θ is the plane angle subtended by the circular aperture at the light-source *

* If the constants had been found by the exact theory, instead of Figs. 2 and 3, we should have obtained NB=35 and μ=0.60. Working back from these more exact values by means of the rigid theory, we find that the calculated curves for τ' and ρ' are almost indistinguishable from those given in Fig. 4. As a matter of fact, this glass (having very small particles) is of such a type as to give almost the maximum difference between the approximate and exact values of the constants.

* It may be noted that, in this expression, an approximate value of the reflection factor ρ' will usually give sufficient accuracy.

The equation shows that the reduction in the light output produced by a given canopy is the more the greater is the value of the reflection factor ρ' for the glass. Also, the reduction increases as the diameter of the aperture increases.

We now see that, by means of this equation, η_0 can be calculated in terms of the glass constants μ and NB, since these give σ and ρ' for any given thickness. It is easy to find by experiment the value of r for a card whose effect is equivalent to any given type of canopy. Furthermore, if this is done, an empirical factor can if desired be found, to allow for the effect due to any particular type of lampholder and support. Having once found both of these, it is then possible to estimate, from a sample of glass, what the performance of a globe made of it will be under practical conditions of use.

It is, however, not often necessary to go as far as this, and it is usually sufficient to determine the values of r which are equivalent to the various types of canopy employed; the values of η_0 referred to any desired r can then be used for the comparison of different globes. These values of η_0 may either have been found directly by photometric measurements on given globes or have been calculated from known glass constants. In the latter case the value of η_0 corresponding to any wall thickness can be found.

Although, up to the present, we ourselves have always determined the glass constants from photometric measurements on small specimens, it would appear to be possible to determine μ and NB from a sample globe, without having to spoil it by removing a piece. The accuracy may not be so great as with the standard method, but in some cases the advantage of leaving the globe intact would outweigh any possible lack of precision. The method is as follows: The value of η_0 is determined as above, using a card of high reflection factor. Then the average value of ρ' can be determined by taking the mean of several observations at different parts of the surface. When taking these measurements, black velvet should be placed inside the globe to exclude light reflected from the far side. A photometer of special design would probably have to be constructed for these measurements. From equation (6) the value of σ then follows. Remembering the expression (5), we see that $\tau' = \sigma(1 - \rho')$, so that we can now proceed to determine the constants, in the manner described in Example 1 of section 6.

As regards the third constant q, which incidentally is only needed when we wish to find the minimum wall thickness to obscure the source, there appears to be no general method of determining it without cutting out a test piece or grinding down a suitable portion. We can, however, determine q, without harming the globe in any way, if it happens to be not too dense to allow a distant lamp filament to be seen through it.

Before going on to show how the theory checks with direct observation, a few general points must be considered. First of all, the theory shows that the effect of non-uniformity of the wall thickness is always to increase the transmission of a globe above the value corresponding to uniform thickness equal to the mean value. The difference is, however, slight, unless the non-uniformity is extreme, such as a variation of 3 or 4 to 1. The distribution of the light will, of course, be different, but the total flux emerging changes only slightly.

Again, it can also be shown that the difference between the transmission factor of a spherical globe and one which does not differ very markedly from this shape is quite small, other things being equal.

Lastly, a word must be said about cases when the glassware has a matt-surface finish. This point was discussed in a previous paper,[11] and we found that the effects of surface finishes, which do not actually contain absorbing matter, should not produce appreciable variations in the transmission factors of globes. This is, however, not the case with opal sheets, so that when determining the constants μ and NB from samples of these special glasses the matt surface should be ground off and the specimen repolished.

We will now show how closely values of η_0 calculated from equation (6) agree with those measured. Four different opal-glassware fittings were obtained, and the values of η_0 were measured for various values of r, corresponding to different types of canopy. Most of the tests were made with a value of r equal to 0.8, on account of the importance of this case in our proposed method of specification, which will be discussed later. The mean thickness X of each fitting was next determined by the simple method given in Part II. Values of η_0 corresponding to these thicknesses were then calculated from the glass constants μ and NB, determined from small samples, in the manner already fully discussed in section (6). In each case the value of θ, for the normal position of the lamp, was 75°.

The results are compared in the last two columns of Table II. The agreement will be seen to be very good.

TABLE II

Fitting No.	Glass constants μ	Glass constants NB	Mean thickness X (cms.)	σ calculated from constants for a thickness X	r	η_0 calculated from σ	η_0 measured directly
1	0·40	14·8	0·15	0·78	0·8	0·74	0·76
2	0·20	6·0	0·24	0·85	0·8	0·81	0·80
3	0·24	4·2	0·19	0·87	0·8	0·83	0·83
4	0·18	3·5	0·22	0·89	0·8	0·85	0·85
4	0·18	3·5	0·22	0·89	0·0	0·73	0·74

It will be noticed that, in the case of Fitting No. 4, η_0 was measured first with a white card of reflection factor 0.8 over the aperture, and secondly, when r was equal to zero. This latter condition was realized in practice by placing over the aperture a stiff card whose inside surface was covered with black velvet; this has a negligible reflection factor. It will be seen that, although the difference between σ and η_0 is, in this case, considerable, the calculated and measured values are in close agreement. The black velvet experiment, in fact, represents the extreme difference between σ and η likely to be experienced with the usual types of canopy, and is therefore an important check on the methods used.

In a further experiment, in which a spherical lamp bulb was used, a piece of glass from another similar bulb was cut so as to fit the aperture where the neck had been removed from the bulb under test. There was thus, in effect, a complete spherical globe of opal glass, and the measured efficiency gave the value of σ directly. The mean thickness of the bulb was 0.093 cms. and the measured value of σ was 0.95. The glass constants were then determined from a sample, and the calculated value of σ for this thickness was found to be 0.96.

The agreement, in the above experiments, between the calculated and measured values is sufficiently good to justify the use of this method of calculation, over the range of values of wall thickness likely to be met with in practice. The method of calculating the value of η_0 at any thickness should prove of value in the design and testing of illuminating ware. We shall, in fact, have occasion to use this method later in the section on specification given in Part II.

The Theory and Specification of Opal Diffusing Glasses.

(Communication from the Staff of the Research Laboratories of The General Electric Company, Ltd., Wembley, England.)

(Paper read at the Joint Meeting of the Illuminating Engineering Society and the Society of Glass Technology, held at Caxton Hall, Caxton Street, London, S.W.1, at 6-30 p.m., on Tuesday, December 13th, 1932.)

(Part II)

By J. W. RYDE, B. S. COOPER and W. A. R. STOYLE

(8) Introduction.

A RÉSUMÉ of the theoretical work on opal glasses, together with a more detailed account of certain of its practical aspects, has been given in Part I of this paper. Here it is proposed to deal, first with the methods of measurement used in the experimental work and the results obtained, and second with certain proposals for the establishment of a figure of merit for opal glasses. Finally, the application of these results to the more recent work of the British Standards Institution Sub-Committee on Diffusing Materials will be briefly reviewed.

(9) The Determination of the Scattering Coefficient q.

The determination of the constant q can only be made on a specimen that transmits an appreciable fraction of unscattered light, that is, such that a distant source, the filament of a gasfilled lamp, for example, can be seen through it. If this is not the case for the specimen available it must be ground down to a sufficiently small thickness and then be repolished.

The specimen is held at some distance from a small bright source of light, rendered approximately monochromatic by means of a filter, and β, the ratio of the brightness of the source, as seen through the specimen, to its actual brightness, is determined. White light must not be used in this measurement, since, in general, q varies rapidly with wavelength. The distance from the light-source must be sufficiently great for the brightness of the surrounding field, due to transmitted scattered light, to be negligible compared with that of the source as seen through the specimen.

The value of β may be determined directly by comparing the brightness of the source, as seen through the specimen, with that observed through a calibrated neutral wedge, or a series of calibrated neutral filters. By changing the monochromatic filter in front of the source, β may readily be obtained as a function of the wavelength of the light.

Alternatively, β may be determined by a spectrophotometric method, but in this case a correction must be made to allow for the forward component of the scattered light which will be superimposed on the beam of strictly unscattered light.

From equation (1) it can be seen that

$$q = \frac{2 \cdot 3}{X} \log_{10} \frac{0 \cdot 92}{\beta} \qquad (7)$$

so that, if β is known for a certain wavelength, and X is measured directly from the specimen, then q may be determined. The value of q which is required is that corresponding to the wavelength, or equivalent wavelength, for which the constants μ and NB are determined, in this case, 5.7×10^{-5} cms. Accordingly β should either be determined directly at this wavelength, or obtained by interpolation from values at a series of different wavelengths.

Fig. 5 shows the variation of q with wavelength for one of the opal glasses measured. A curve has been drawn through the experimental points, and it can be seen that the value of q for this glass, at a wavelength of 5.7×10^{-5} cms., may be taken as equal to 70.

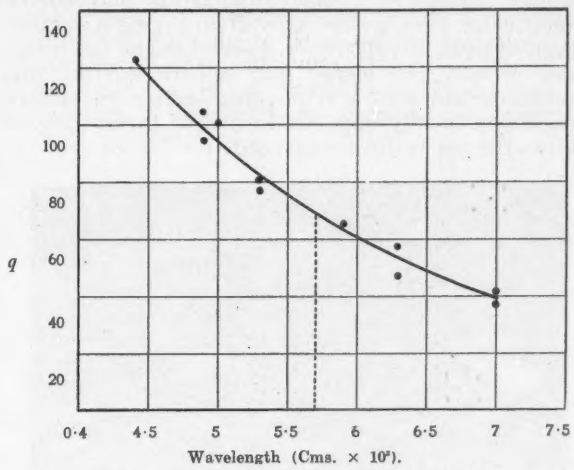


Fig. 5.—Variation of q with wavelength; glass M.

The above fundamental methods for obtaining q are somewhat elaborate, but the following simple substitution method may be used in practice whenever a number of glasses are to be measured.

A sheet of some opal glass, known to be fairly uniform in quality, is selected and ground into the form of a wedge about 5 cms. long and then polished. The thickness should diminish uniformly from about 2 mm. to zero, and the type of glass chosen should be of a relatively lightly diffusing variety, so that the filament of a distant gasfilled lamp is only just indistinguishable through the thickest part of the wedge. By means of one of the above methods, the value of q for the glass composing the wedge is determined. Of course, this should be independent of the thickness, but in case there may be any variation in the quality of the glass from one end to the other, q may be found for different positions and a calibration curve plotted. It is probable, however, that, if the glass has been chosen carefully, the variations can be neglected. This fundamental value of q is to be found for the desired standard equivalent wavelength.

When the value of q is required for a sample of any other glass, the given specimen is, if necessary, ground down and repolished to a suitable thickness. A position is then found on the wedge such that the filament of a distant lamp appears equally bright when viewed through either the wedge or the sample. Under these conditions, the values of qX are equal. But since the thickness of the sample and that of the wedge at the above point are known, as is also the value of q for the wedge, the unknown q for the sample follows immediately, and will refer to the effective wavelength, stated above, for which the wedge was calibrated.

The above comparison can, in practice, generally be made without using colour filters, since the change in the colour of the source produced by different glasses, having the same value of qX, is usually small.

(10) The Measurement of the Total Transmission Factor and the Reflection Factor of a Flat Sample.

The determination of τ' and ρ', the total transmission and reflection factors, is made from measurements on small circular specimens cut from the glass under investigation, the specimens being ground down to parallel-sided discs of suitable thickness and then polished.

The apparatus used[13] for the measurement of these factors consists of a small integrating photometer comprising, first, an optical system giving a parallel beam of light of variable cross-section and intensity, and, second, an integrating sphere having two apertures and also a removable section of sphere wall diametrically opposite to one of them. Fig. 6 shows the apparatus set up ready for use.

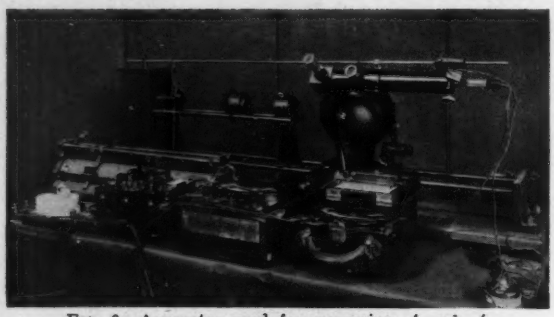


Fig. 6.—Apparatus used for measuring τ' and ρ'.

As mentioned in Part I, the transmission and reflection factors depend on whether the incident light is parallel or diffuse. In the present simplified method of applying the theory, only the more easily determined pair of values τ' and ρ', which refer to parallel incident light, need be known.

(i) *Measurement of the Total Transmission Factor* τ'.

A parallel beam of light is projected through the aperture A into the sphere (see Fig. 7). The brightness of the sphere wall is measured by means of a photometer viewing, through the second

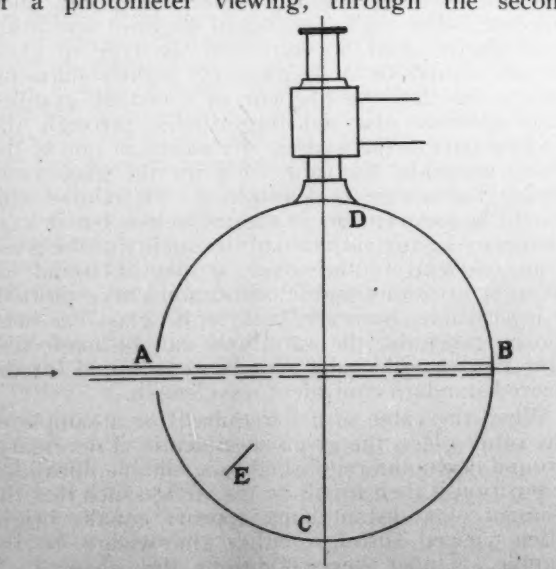


Fig. 7.—Showing arrangement of Sphere for Measurement of Transmission Factor.

aperture D, a point C. The specimen is then inserted in the aperture A, and the brightness of the sphere wall at C again determined. A screen E, interposed between the specimen and the point C, prevents light from the former reaching C without at least one reflection from the sphere wall. The ratio of the second brightness measurement to the first gives the value of the total transmission factor τ'.

(ii) *Measurement of the Reflection Factor* ρ'.

As in the first experiment, a parallel beam of light is projected through the aperture A, and the sphere wall brightness measured. The specimen is now substituted for the removable section of sphere wall B, and the screen E transferred so that it occupies a position so as to screen C from B. A second brightness measurement is now made. The ratio of the second measurement to the first gives the value of the reflection factor ρ'.

With cased and flashed opals, accurate values of the constants can be obtained only by using samples from which the clear glass portion has been ground away. Such a method is usually impracticable, but we have found that sufficiently accurate values of the constants for the opal glass may be determined by measuring τ' and ρ' on a sample composed of both clear and opal layers. It should be noted that the value of X to be used, when applying the curves, is the thickness of the opal glass layer alone, and not the total thickness of the sample. The most accurate values of the constants are obtained when ρ' is measured with the sample so arranged that the layer of opal gleass is towards the incident light. When measuring τ', it is immaterial which way round the sample is placed.

It is particularly important that, in the determination of ρ', the specimen under test should not be mounted absolutely at right angles to the incident beam. This will ensure that light which is reflected specularly from the polished surface of the glass specimen does not emerge from the aperture through which the light enters.

In the more usual form af this apparatus, as employed by a number of other investigators,[14,15] the specular reflection from the surface of the glass emerges through an aperture in the integrating sphere. Similarly in the transmission test, the light transmitted unscattered emerges from the integrator through another aperture diametrically opposite to the specimen. In the present work, however, the equations on which the curves in Part I have been based include the specularly reflected and unscattered transmitted light. Thus it is essential that the apparatus should be so designed as to include these quantities in the measurements.

There is one further point that may be mentioned here. It has been pointed out[16, 17] that certain errors are introduced in the measurement of τ' and ρ', when using this type of apparatus, by the necessary alteration in the conditions inside the sphere due to the introduction of specimens into the apertures. This error is a function of the relative dimensions of the apertures and the whole sphere, and also of the reflection factor of the sphere wall coating.* We have found that in the particular apparatus used, the reflection factor of the sphere coating and the size of the apertures are such that these errors are very small, and do not materially affect the values of the optical constants obtained from the photometric measurements.

The experimental details involved in measurements using this apparatus, and the conditions which have to be fulfilled in order to obtain reliable results, are given in the paper by Waldram,[13] reference to which has previously been made.

Having now measured the values of τ' and ρ' for the specimen, its thickness X is determined; then the constants μ and NB for the glass may be found by using the curves given in Part I. Since, with change of wavelength, the variation in the values of μ and NB is small, the measurement of τ' and ρ' may be

* This error becomes very large as the reflection factor of the sphere wall coating aproaches unity, and also as the area of the aperture becomes an appreciable fraction of that of the sphere surface.

made using the light from a gasfilled electric lamp, for example; the values so obtained may then be taken to refer to the equivalent wavelength of 5.7×10^{-5} cms.

(11) The Determination of the Mean Wall Thickness of a Globe.

For some purposes we need to know the mean wall thickness of the glassware of a fitting. A very simple method of determining this is as follows. We have found from numerous tests that the density of most opal glasses is, quite closely, 2.5 grams per c.c. Assuming this value, it is then only necessary to weigh the globe and to find its surface area. The latter can be obtained in various ways, directly from measurements, for example. The mean thickness X is then given by

$$X = \frac{0{\cdot}4\,w}{A} \qquad (8)$$

where w is the weight in grams and A is the surface area in square centimetres.

It will be realized that it is only necessary to determine the surface area of a given type of globe once and for all; the mean thicknesses of all similar globes can then be found immediately from their weights.

As a check on this method, certain opal fittings were cut into sections, and the mean thickness directly determined for each by making a large number of micrometer measurements along the edges of the sections. Values of X obtained in this way were found to be in close agreement with those obtained by the above simple method.

A section of a typical globe, suitable for a 100-watt lamp, is shown in Fig. 8. It will be seen from this that the thickness varies from 0.138 to 0.352 cms.

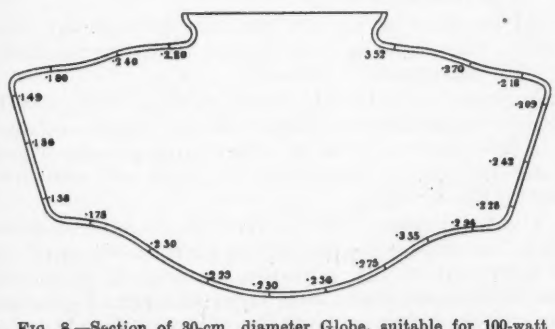


Fig. 8.—Section of 30-cm. diameter Globe, suitable for 100-watt lamp. The thickness at various points is given in cms.

(12) The Glass Constants.

The following table gives, for a number of glasses, the values of the three constants μ, NB and q, which have been determined in the manner described above.

TABLE III

Glass Constants referred to an equivalent wavelength of $5{\cdot}7 \times 10^{-5}$ cms.

Glass	μ	NB	q
A	0·18	5·3	230
B	0·25	4·5	130
C	0·21	7·4	80
D	0·20	6·0	110
F	0·37	1·05	28
G	0·44	0·55	18
H	0·13	10·8	230
J	0·18	6·2	230
K	0·40	14·8	120
L	0·62	32·0	195
M	0·21	3·6	70
N (flashed)	1·1	30·0	1400
P (cased)	0·36	7·3	160

With few exceptions, notably N and P, which are flashed and cased opals respectively, the glasses referred to in the table are ordinary pot opals. All except L, which is many years old, are of comparatively recent manufacture.

As regards the variation of the constants corresponding to different batches of the same type of glass, made at different times, we have generally observed that these are fairly small. This may be illustrated by Table IV which shows the values obtained from tests made on deliveries, from one manufacturer, extending over a period of about 12 months. As a matter of fact, the variations over samples taken from the same batch are often nearly as great as those found in different batches. Changes of this order of magnitude are, in general, quite unimportant.

TABLE IV

Test	μ	NB	q
1	·19	6·6	80 to 110
2	·21	7·2	
3	·17	6·7	
4	·20	6·0	

Quite apart from the use of the constants to calculate the various optical properties corresponding to different thicknesses of the glasses, a considerable amount of other information concerning the intrinsic qualities of the opals themselves can be derived from μ, NB and q. This information, it is hoped, will be of value to the manufacturer, especially when the conditions controlling the size and number of the particles which separate out become more fully understood.

The constant μ, it will be remembered, is an absorption coefficient, so that glasses having a high value of μ will absorb more useful light than those having lower values. Our experience indicates that, to be efficient, pot and cased opal glasses for use in lighting fittings should certainly not have a value of μ in excess of 0.25. Typical glasses which are unsatisfactory in this respect are K, G and L. The importance of a low value of this constant may be seen from Fig. 3a, which shows how, for a given thickness, the value of σ and therefore of the light output ratio of a globe decreases as μ increases We have seen that, in opal glassware, much of the incident light has to travel backwards and forwards through the glass before emerging. It follows from this that the reduction in transmission, due to the presence of a given amount of absorbing material, will be much greater for an opal than for a clear glass. If, therefore, a manufacturer finds that the value of μ is high, for an otherwise good glass, he should make every effort to reduce the amount of absorbing material, such as iron, which may be present. The addition of manganese as a decolourizer will, of course, only make matters worse.

Now let us turn to the remaining constants q and NB, which are both directly related to the particles present in the glass. It is of interest to note that the ratio q/NB will remain constant when we alter the number but not the size of the particles. This is because both constants vary in direct proportion to the number present per unit volume. On the other hand, any change in the size of the particles will occasion a corresponding change in the ratio q/NB. The relation between this ratio and particle diameter has been fully worked out for spherical particles,[9] but we shall not stop to discuss this here. As a very rough rule it may be said that according as this ratio is greater or less than 12 so will the average particle diameter be above or below one thousandth of a millimeter. This assumes that the range of sizes present is not too great.

From a glance at Table III we can thus say that glasses K and L have small particles, while N and F have large ones. Thus, the value of q/NB for glass K is 8.1, and the average observed particle diameter is 0.45×10^{-3} mm., while for glass N the ratio q/NB is 46.6 and the average diameter about 4.0×10^{-3} mm.

Considering the correspondence between these constants and the optical behaviour of the glass, we may say that q is a scattering coefficient relating to the amount of light diffused by the particles in all directions, while, roughly speaking, NB is related to the amount scattered by them in backward directions only. Thus, the greater the value of q, the more completely will a given thickness of glass obscure the light-source, while the greater the value of NB, the larger will be the fraction of the incident light reflected.

The above considerations enable us to form some idea of the best values of the constants to meet various practical requirements. Thus, if we intend to use the glass as a reflector, there is no question of the light source being visible through it, so that the value of q is immaterial, but, as mentioned above, the constant NB should be as large as possible. It follows that, of the glasses in Table III, we should choose L or N for the above purpose.

To illustrate this case, Table V shows the set of glasses arranged in order of their reflection factors ρ' corresponding to sheets 0.2 cm. thick.

TABLE V

Reflection and Transmission Factors, ρ' and τ', for sheets of thickness 0·2 cm.

Glass	μ	NB	ρ'	τ'
L	0·62	32·0	0·70	0·13
N	1·10	30·0	0·64	0·11
K	0·40	14·8	0·62	0·26
H	0·13	10·8	0·61	0·35
C	0·21	7·4	0·53	0·40
P	0·36	7·3	0·51	0·38
J	0·18	6·2	0·51	0·44
D	0·20	6·0	0·50	0·44
A	0·18	5·3	0·48	0·46
B	0·25	4·5	0·45	0·48
M	0·21	3·6	0·42	0·51
F	0·37	1·05	0·29	0·59
G	0·44	0·55	0·24	0·62

It will be seen from this table that, in a general way, for thicknesses such as this, the order of the glasses is the same for ρ' as for NB. Such a statement is, however, not strictly true because it leaves out of account the effect of μ. The influence of this constant is, in this case, not great, but it may reverse the order of two glasses having nearly equal values of NB.

From the last column of the table we see that much the same applies to the transmission factor τ', except that now the values are in the reverse order. The action of μ is here slightly more important, and it has upset the regular order in the case of glasses C and P, for example.

Of course, the best transmission will be obtained when NB is zero; in other words, when there are no particles there at all! In practice, however, we generally need the diffusion of the light to be as complete as possible, and to assess this we must bring in the value of q. To do this $(qX)_v$ must be calculated; the suitable equation similar to (2), Part I, has already been given.[12] We shall not, however, develope this point further, as much the same conditions occur in the next problem we have to consider.

The case of globes, when the condition is laid down that the light-source is not to be visible, is perhaps of even more general interest. If, in making the glass, we had complete control over the size and number of the particles, we should proceed as follows:—

In the first place, we must naturally reduce μ as much as possible. But since, in spite of all precautions, there will always be some absorbing material present, it follows that, for maximum transmission, the globe should be blown as thin as its mechanical strength will safely allow, and then the diffusing power increased until the source is just obscured. Next, it is easy to see that NB must be low, since otherwise the reflection factor of the glass will be high and much of the light from the lamp will be reflected back into the interior of the globe instead of being transmitted directly. Hence we must adjust the value of q to the minimum value necessary to obscure the light-source and, at the same time, make NB as low as is consistent with this.

Now we have seen that the ratio q/NB increases with particle size, so that, for a given value of q, it follows that to make NB small we must have large particles. In our experience they should be not less than one or two thousandths of a millimetre in diameter.*

To sum up, the optimum conditions are thus:—

(1) Wall thickness as small as is practicable.

(2) Impurities causing absorption to be reduced to a minimum.

(3) The value of q must be near to that corresponding to $(qX_v)/X_o$ where the numerator is given by equation (3) and X_o is the smallest thickness likely to occur anywhere on the globe.

(4) The value of NB must be as low as is consistent with (3). That is, the particles should be large.

(5) In place of (4) we can just as well say that the ratio q/NB should be large; greater than 15, for instance.

A glance at Table III shows at once that glass L is quite unsuitable for globes, since $\mu = 0.62$ and also q/NB is only 6.1. On the other hand, glasses A and J are very good, since their μ values are very low and q/NB is high.

The conditions which we have just established are useful as showing what values of the constants are to be aimed at. If, however, we wish to decide on the relative suitability of a large number of glasses, the values of the constants themselves will only serve as a basis for a very broad classification into good, bad and indifferent types.

The reason is that there are three constants concerned, and it is often impossible to see at a glance just what their combined effect on the performance of the glass will be. In order to overcome this difficulty a scheme was devised[12] whereby a single figure of merit for each glass could be determined; this then allows any number of glasses to be compared and arranged in order of their suitability. We shall discuss this in the following section.

(13) The Figure of Merit of Diffusing Glasses to be Used for Globes.

We cannot assess the relative suitability of various glasses (to be used in the form of globes for lighting fittings) by knowing only the light output ratio of a sample fitting of each type. A globe of a really good glass may have been blown with too great a wall thickness while another, giving a very high light output ratio, may not adequately obscure the

* There does not seem to be much advantage to be gained by going to diameters distinctly greater than this. The theory indicates that the additional gain is small, and in practice it seems difficult to get much larger particles without also forming a quantity of very small ones.

light-source. Again, the particular canopy used will, in each case, affect the results.

In order to overcome these difficulties we propose to take as the figure of merit the value of σ corresponding to the particular wall thickness most suitable for each glass; provided that this thickness is not less than that consistent with adequate mechanical strength.

It will be remembered that σ is the transmission factor for a complete spherical globe enclosing the light-source and that, if the glass constants are known, its value can be determined immediately from the curves given in Fig. 3.

The figure of merit f of a glass, to be employed as a globe in lighting fittings, will be defined as the value of σ corresponding to the least wall thickness which will completely obscure the light-source and at the same time give adequate strength. Let X_v be the thickness which only just prevents the source being seen through the glass and X_o the minimum thickness to give sufficient strength.[12] Then we can say, more briefly, that the figure of merit f is the value of σ determined for a thickness equal to whichever is the greater of X_v and X_o.

Strictly, of course, this means that the figure of merit will depend upon the size and shape of the globe and on the type of lamp with which it is intended to be used. We have already seen that changes in shape do not affect σ to any great extent, so that this factor can be neglected for our present purpose. With electric lamps, equation (3) shows that the value of $(qX)_v$ varies very little for the various pairs of values of wattage and globe diameter used in practice. This is because for larger lamps correspondingly bigger globes are used, so that $\log (d^2/W)$ changes very slightly. In the present case it will therefore be sufficient to take $(qX)_v = 12.8$. The same arguments will apply to other illuminants, but, for these, new values of $(qX)_v$ must be determined. The value of X_v is obtained immediately from $(qX)_v$ by dividing this by the constant q for the glass.

Now as regards X_o, measurements which we have made on a large number of fittings show (see next section) that the minimum mean wall thickness necessary to give adequate strength is about 0.13 cm., so that we shall adopt this value.

As an example, we shall find the figure of merit for glass A. Since, from Table III, $q = 230$, we obtain $X_v = 0.056$ cm. Then, since this is less than the fixed value of $X_o = 0.13$ cm., we determine σ, for a thickness equal to X_o, by Fig. 3. The value comes out to be 0.935, and is the required figure of merit.

Again, in the case of glass C, $q = 80$, so that $X_v = 0.16$, which is greater than X_o. In this case, therefore, f is given by the value of σ corresponding to a thickness of 0.16 cm.

The values of f, obtained in the above manner, for all the pot-opal glasses are given in the following table:—

TABLE VI
Figure of Merit for Pot Opal Glasses
$X_o = 0.13$ cm. $(qX)_v = 12.8$

Glass	q	X_v cms.	μ	NB	Thickness at which f is calculated	Figure of Merit f
A	230	0·056	0·18	5·3	X_o	0·935
B	130	0·099	0·25	4·5	X_o	0·915
C	80	0·160	0·21	7·4	X_v	0·89
D	110	0·117	0·20	6·0	X_o	0·925
F	28	0·46	0·37	1·05	X_v	0·67
G	18	0·71	0·44	0·55	X_v	0·50
H	230	0·056	0·13	10·8	X_o	0·945
J	230	0·056	0·18	6·2	X_o	0·93
K	120	0·107	0·40	14·8	X_o	0·82
L	195	0·066	0·62	32·0	X_o	0·64
M	70	0·183	0·21	3·6	X_v	0·895

It will be seen that glasses A, F, H and J have an exceptionally high figure of merit and thus are the most suitable. In fact, it might well be laid down by the user that the glass must have a figure of merit greater than, say, 0.90. It will be noted that all the glasses whose f is greater than this have a low value of μ.

So far we have only considered pot opal glasses but, with a few simple modifications, the figure of merit can, in addition, be found for flashed and cased opals and also for those having matt surface finishes; the method is thus quite general.

In the case of flashed and cased opals, the question of a minimum thickness to give adequate strength does not concern us, so that X_o must now refer to the minimum thickness of flashing that can be satisfactorily produced. We have not yet sufficient data to lay down this figure but, once it is established, the procedure to find f is the same as that already given for pot opals. Sufficiently accurate values of the constants for this purpose may be determined by the method described in Section 10, but it should be remembered, when using Figs. 2 and 3, that X now refers to the thickness of the opal layer and not to the total thickness of glass.

When either the internal or external surface of the globe is treated to produce an etched or other type of matt finish, the question of filament visibility hardly arises. It follows that, in this case, the optimum performance will be obtained when the thickness is equal to the appropriate value of X_o, so that the figure of merit will always be the value of σ corresponding to this thickness. The glass constants should always refer to the opal glass itself and they should be determined from measurement on a sample having the light incident on the polished surface. We have shown that under this condition, Fig. 3 may still be used to find the constants and then the value of f. It may be noted that, in this particular case, a determination of q will not be necessary.

(14) A Proposed Method for the Specification of Opal Glassware for Lighting Fittings.

In August, 1929, and January, 1931, reports on our theory were presented to the British Standards Institution Sub-Committee dealing with Diffusing Materials. Since, at this time, the existing British Standard Specification on Translucent Glassware Illumination Fittings[18] was under revision, it was thought that it might be possible to amplify this specification in the light of some of the results obtained during the course of the work described above.

The only reference in the existing specification to the performance of a fitting is in Clause 11, which says that the efficiency shall be stated by the maker, and the actual efficiency shall not differ from this by more than ± 15 per cent. of the stated value. Thus there is no check on the quality of the product produced, but only on its limits of variation.

This was not at all adequate, and the first suggestion that was considered was that the quality of the actual glass used (as defined in some manner by the values of its optical constants) might be specified.

A lower limit for the figure of merit, for example, might be laid down, but this needs somewhat lengthy measurements, and probably would entail the destruction of the fitting. This method is thus impracticable. The use of the figure of merit is, of course, valuable for selecting the most suitable out of a number of types of glasses which might be used for a given purpose, but it was clear that it could not form the basis of a simple specification.

All opal fittings of necessity occasion a certain loss of light and the value of the specification to the

user is to ensure that this loss shall not be unnecessarily high. It follows that the specification should state a lower limit for the light-output ratio of the fitting; but clearly this must be measured under some standard conditions. It will be seen, moreover, that this alone is not sufficient, because the manufacturer of a bad glass has only to blow his globes sufficiently thin in order to raise their efficiency above the limit proposed. The fittings would then be unsatisfactory on account of fragility. Again, even if they were strong, they would probably allow the filament of the lamp used to be seen. We thus arrive at the necessary conditions.

(1) The efficiency, when measured in a specified manner, must be greater than a given value.

(2) The thickness must not be less than a certain minimum.

(3) The light-source must not be visible through the globe.

As soon as it was attempted to define these conditions more fully and to fix the limits, it was realized that the matter was by no means as simple as it appears at first sight. It will be seen that if one universal lower limit for efficiency were laid down for all types of fitting, it would have to be fixed at a low value in order to include the types whose form is such as necessarily to lead to poorer efficiencies. But this limit would not then keep up the standard of the intrinsically more efficient types. It also appeared at first sight as if the lower limit of thickness would be dependent on the size and nature of the fitting.

The basic proposal seemed to be sound, but it was quite clear that a considerable amount of work would have to be done before a simple form of specification could be evolved. This work we undertook to carry out, and the results showed that several simplifications could be made, which were not apparent when the problem was first attacked.

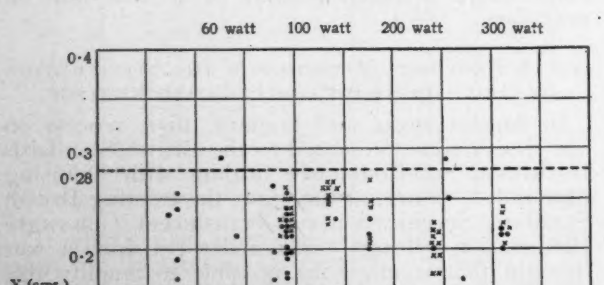


FIG. 9.—Mean Thickness of Glassware.

* Glassware of very recent manufacture.

* Representative samples collected over a period of several years, including a certain number of uncommon forms.

It was decided first to investigate the variation of mean wall thickness with size and type of fitting. The results are shown in Fig. 9, where the thickness of the globes is plotted against the surface area. About eighty fittings were measured, their diameters ranging between 15 and 40 centimetres. The globes included specimens of about 14 different types, both of British and foreign manufacture, and were chosen to be as representative as possible.

From these results the important facts emerged that the average mean thickness of any type of fitting is practically independent of the size while, for almost all the fittings, the mean thickness was found to lie between the limits 0.13 and 0.28 cms. It appears, therefore, that it will not be unreasonable to take 0.13 as the required lower limit of mean thickness for all normal sizes of fitting.

Remembering the method, described in section 11, for finding the mean thickness, it will be seen that the minimum thickness clause can now be put in the following simple form: The mean thickness of the glassware, determined by the following formula—

$$0{\cdot}4 \times \frac{\text{weight of globe in grams}}{\text{surface area in sq. cms.}}$$

shall not be less than 1.3 mm.

The question now arises as to how to determine the lower limit of light-output ratio to be specified. This cannot be done by measuring its value for a large number of representative fittings and then deciding on an arbitrary minimum value for acceptance. There are several reasons for this. First, unless due allowance were made for the effect of different types of canopy, this would be no criterion of the performance of the globes themselves. Some standard method of measurement, which would eliminate the effect of the canopy, would therefore have to be laid down. Second, even with such a system, there would still be the difficulty due to the fact that some forms of globe, those with large apertures, for example, are bound to give a relatively low value of the light-output ratio. A limit imposed to allow for these would be unnecessarily lax for those with small apertures.

It was realized that both of these difficulties could be eliminated if, instead of trying to fix a universal minimum of the light-output ratio, we made this restriction apply to σ. This latter, it will be remembered, is the ideal light-output ratio which would be obtained if the globe were without apertures, spherical in shape and of uniform wall thickness.

We have already shown in Part I, Section 7, that there is a simple relation between σ and η_0 the light-output ratio measured under certain easily realizable conditions, which do not differ greatly from those obtaining in actual use. Thus, once a universally applicable lower limit to σ has been laid down, corresponding limits of η_0 for all the various cases can immediately be calculated by equation (6), if the size of the aperture and the reflection factor r of the card placed over it are known, together with the value of ρ' for the glass.

The necessity of knowing ρ' and r makes this step inconvenient for specification purposes, but further work has shown how the difficulty may be overcome. The essential advance was made by realizing that if we lay down the condition that η_0 is to be measured with the aperture covered by a white plate or card of high reflection factor, likely variations in ρ' become unimportant.

Hence, if we specify the reflection factor of the card, the necessity for any calculation is obviated, since a small table can be drawn up giving the relation between η_0, measured under the above condition, and θ the plane angle subtended by the aperture at the light-source.

By this procedure we secure another most important advantage. This is that the error in the measurement of η_0, due to any slight variations in the position of the light-source, is less the higher the reflection factor of the card covering the aperture. Thus, with a black cover, a change of 1 in. in the distance of the lamp filament from the aperture produced a change in η_0 from 0.67 to 0.73, while, with a white card of reflection factor of 0.8, a similar change in distance only altered the value of η_0 from 0.845 to 0.85.

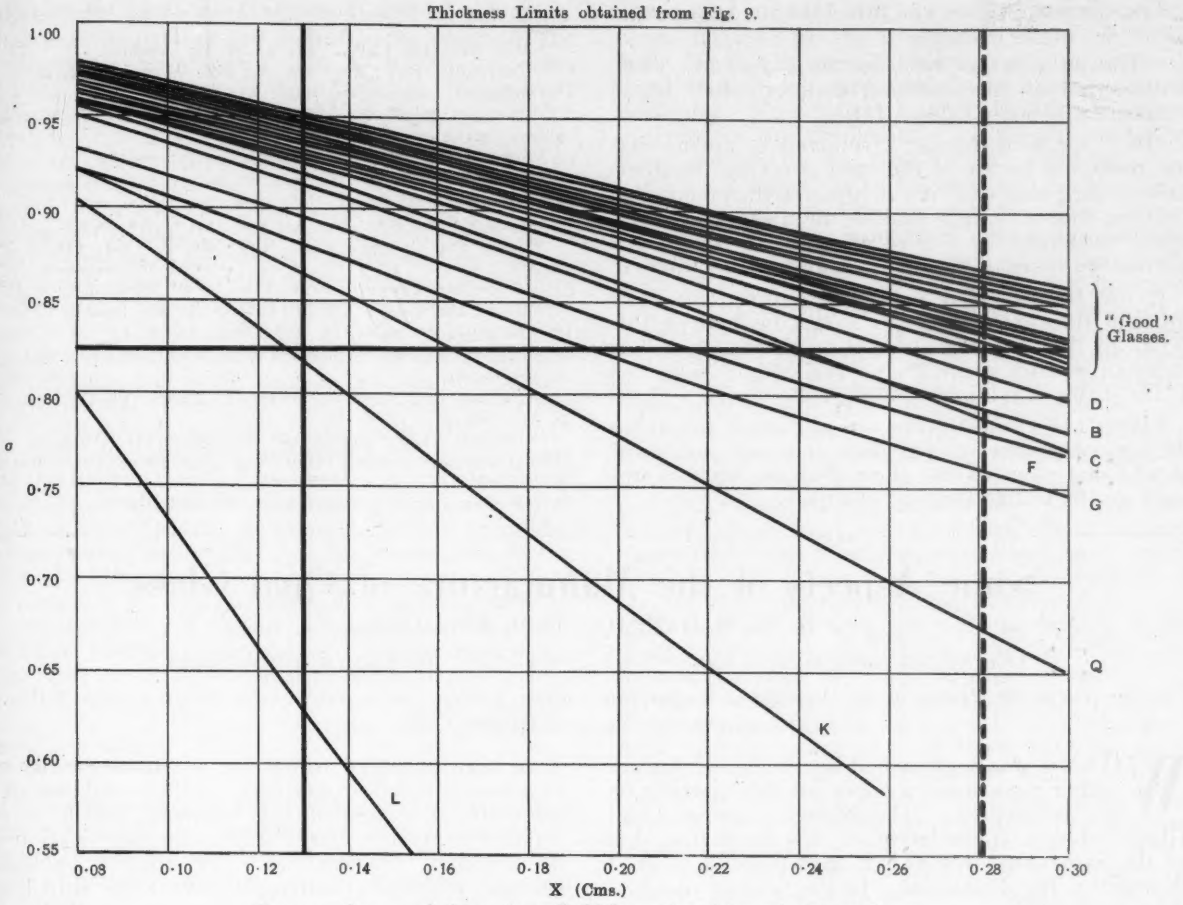


FIG. 10.—Curves relating σ to wall thickness for globes of various glasses.

The actual values of the limits were fixed in the following way: The constants μ and NB were determined for a large number of representative glasses and, by means of these, curves connecting σ with wall thicknesses were determined. The results are shown in Fig. 10. Curves representing good modern glassware, produced by a number of makers, all fall close together towards the top of the diagram. Of the curves falling below these, some are of quite recent manufacture, and others represent the production of some few years ago. The lettering corresponds with Table III, which gives the glass constants.

After careful consideration it was decided that a suitable minimum value of σ would be 0.825, since curves for all the "good" glasses lie above this value over the whole of the practical range of wall thicknesses. This does not reject all the other glasses entirely, since, as will be seen from the figure, a globe made from glass B, for example, will be satisfactory in respect of its light-output ratio, provided that its wall thickness is less than 0.24 cm.

We now need to choose the value of the reflection factor r of the card to be used over the aperture when measuring η_0. For the reasons already given, the value of r should be greater than 0.7, say. Now "Bristol board" is a convenient and accessible material, and measurements showed that its reflection factor, when clean, is round about 0.80. The standard reflection factor for the aperture card was fixed at this value, so that for all but critical tests, "Bristol board" may be employed.

Having fixed the lower limit of σ and the value of r, the corresponding lower limits of η_0, for various values of θ and ρ', can now be deduced from equation (6). The results are given in Table VII for three values of ρ' covering the likely range.

TABLE VII
Values of η_0 for $r = 0{\cdot}80$

θ	Values of η_0 for a representative range of glasses			Mean values of η_0
	$\tau' = 0{\cdot}35$ $\rho' = 0{\cdot}578$	$\tau' = 0{\cdot}45$ $\rho' = 0{\cdot}458$	$\tau' = 0{\cdot}55$ $\rho' = 0{\cdot}337$	
0°	0·825	0·825	0·825	0·825
20°	0·824	0·824	0·824	0·824
40° (Practical Range)	0·813	0·814	0·816	0·814
60° (Practical Range)	0·795	0·802	0·806	0·801
80° (Practical Range)	0·777	0·788	0·793	0·786
100° (Practical Range)	0·747	0·764	0·773	0·761
120° (Practical Range)	0·708	0·733	0·747	0·729

The values of η_0 for this range of ρ' are now seen not to differ greatly from the mean values given in the last column of the table. It appears, therefore, that the measurement of ρ' in each case is unnecessary, so that the lower limits of η_0, corresponding to the fixed values of σ and r, can be obtained directly from the following simple table:—

TABLE VIII

Angle subtended by the diameter of the opening at the light-source, when in its correct position	Light-output ratio to be greater than the figures given below when the opening is covered with a flat sheet of an opaque material whose diffuse reflection factor is not greater than 0·8
0°	0·825
20°	0·82
40°	0·81
60°	0·80
80°	0·78
100°	0·76
120°	0·73

A little consideration will show that this same table is also applicable to both flashed and cased opal glasses.

The efficiency clause can now take the very simple form:—

The light-output ratio of the glassware, when measured in the specified manner, shall be in accordance with Table VIII.

The "specified manner" referred to means that the reflection factor of the card covering the aperture of the globe shall not be greater than 0.80; also that the source of light shall be an uncapped electric lamp, suspended by fine wires, so as to occupy the normal position of the lamp employed in practice.

It will be seen that if, at any future date, it is thought desirable to stiffen a specification of this type, all that need be done is to decide on a new value of σ from which the corresponding values of η_0 for Table VIII immediately follow.

Finally, to complete the set of clauses involving the optical qualities of the glass, it is only necessary to add one more to the effect that the light-source shall not be visible through the globe.

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Some Aspects of the Manufacture of Opal Glass

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(*Paper read at the Meeting of the Illuminating Engineering Society, held at Caxton Hall, Caxton Street, London, S.W.1, at 6-30 p.m., on Tuesday, December 13th, 1932.*)

WHEN I was approached by Professor Turner with a request for a paper for this meeting on the subject of "The Manufacture of Opal Glass," I was appreciative of the distinction, but at the same time somewhat apprehensive when I thought of the difficulties. In the Society of Glass Technology there are many specialists on manufacture, and one is diffident in preparing a paper on that subject unless one is in a unique position, such as we occupy in the manufacture of optical glass, or unless one has the advantage of a considerable time in which to circulate other manufacturers in order that the paper may be comprehensive and representative. Unfortunately, it was impossible to have time for such enquiries, and therefore if my remarks seem to apply too markedly to manufacture in our own works I trust I shall be forgiven. Another point which carried some weight with me was that this is a joint meeting of the Society of Glass Technology and the Illuminating Engineering Society. The knowledge of this simplified the task to some extent, since I hoped that when I was saying things which were elementary to the members of the one Society, I might at the same time be giving information which was not common knowledge to the members of the other.

The manufacture of opal glass in this country has increased very rapidly in importance during the last three or four years, and particularly during the last twelve months. There are several reasons for this, such as fluctuations in the rate of exchange which have diminished the intensity of competition from abroad; the general tendency during recent years to "Buy British"; and, not less important, the knowledge of the underlying properties of opal glass which has been discovered and on which British manufacturers have been quick to base developments.

Considering first the manufacture of opal glass for lighting fittings, the tendency during recent years for light-sources of higher brightness has created an improved demand for globes of diffusing material in order that the effective brightness of the source may be reduced to comfortable values. At the same time, as little light must be lost in this process as is humanly possible, and so specifications have been prepared which are based essentially on two fundamental properties: (1) the avoidance of a geometrical image of the filament, which is an attempt to restrict glare; and (2) the specification of a minimum transmission for totally enclosed fittings, which is an attempt to limit the light loss.

Some three or four years ago we were called upon to carry out experimental work on the development of a suitable opal glass for lighting fittings, primarily electric lighting fittings, to comply with these two requirements. At that time it was stated in the trade generally that pot opal glasses could not compare with flashed (either two- or three-ply) opal globes on the ground of light transmission. This was true, but we did not feel that it was inevitable. We had to make some decision as to the criterion by which our experimental progress should be measured, and we decided provisionally that a measure of the brightness of a small specimen in different angular directions to an incident beam of parallel light would give us a good measure of the diffusion, and that the light output ratio for a globe would give the other necessary figure. We did not realize then the importance of the various factors which have since been elucidated by the work of Messrs. Ryde and Cooper, and our methods were, in the light of present knowledge, somewhat rough and empirical.

As a result of experimental meltings and measurements on the lines suggested above, we were able to come to certain definite conclusions. For instance, it was found that the addition of tin oxide, while giving a marked increase in opacity, unfortunately at the same time reduced the light-output ratio by some 8 per cent. A change from soda to potash increased slightly the opacity for a given concentration of fluorine. The substitution of boric acid for silica gave an increase in light-output ratio of about 8 per cent., but only did this by decreasing the opacity so that the direct light transmission was seriously increased. These results are partly explicable in the light of Ryde and Cooper's[1] theoretical work. The scattering coefficient for a given particle size and number is proportional to the square of the

[1] J. W. Ryde and B. S. Cooper, "The Scattering of Light by Turbid Media." Proc. Roy. Soc. A 1931, 131, 464.

ratio of the difference of the squares of the refractive index of the particle and matrix to the square of the refractive index of the matrix. Thus, if the index of the glass matrix be kept constant, the greater the refractive index difference of the particles the better. For this reason, sodium fluoride is preferable to calcium fluoride and potassium fluoride to sodium fluoride, purely on the basis of refractive index. The effect of these changes in the refractive index of the matrix must be considered. Now Ryde and Yates[2] have also shown that no sodium fluoride separates out when the concentration of sodium oxide is less than about 8 per cent. These two facts partly explain the difficulty of obtaining sufficient opacity in the presence of boric oxide, and borosilicates are necessarily used for glasses of relatively high thermal endurance. This necessitates the use of low concentrations of sodium oxide, and hence of small precipitations of sodium fluoride. Thus, part of the difficulty with borosilicates is only indirectly connected with the boric oxide, but since borosilicate glasses are, in general, low in refractive index, even the particles that are precipitated do not give as high a scattering effect as in a soda-lime mixture. If one considers a soda-lime glass of refractive index of 1.52 and a borosilicate of 1.49, the relative scattering powers for the same number of particles of the same diameter would be:—

	Calcium Fluoride	Sodium Fluoride
Soda Lime Glass	2	8
Borosilicate Glass	1	6

These differences, however, while important, do not compare with the variations in scattering power which may be achieved by alterations in particle size. The following figures are of interest. If one assumes:—

(*a*) That the total volume of particles be constant; or (*b*) that the total number of particles be constant; then the relative scattering powers are:—

	Constant Volume	Constant Number
D = .2 × 10^{-4} cms.	125	1
.5 × 10^{-4} cms.	690	87
1.0 × 10^{-4} cms.	1,730	1,730
2.0 × 10^{-4} cms.	3,470	35,000

The importance of large particle size can therefore scarcely be overestimated. Further work is clearly desirable on the relations between composition, heat treatment and particle size.

It is of interest to compute the amount of soda, lime and fluorine in the precipitated particles in opal glass. Thus, in Ryde and Cooper's work the glass was found to contain 1.5 × 10^{12} particles per c.c., with a mean diameter of 3.5 × 10^{-5} cms. The total volume of the particles, assumed to be spheres, is therefore 3.4 × 10^{-2} c.c per c.c. or 3.4 per cent. by volume.

The density of the particles is not very different from that of the matrix, so that, considering the assumptions involved in the calculation, a correction to bring the figures to percentage by weight is unnecessary. It was estimated that 40 per cent. of the particles consisted of calcium fluoride and 60 per cent. of sodium fluoride. Thus it may be computed that the glass contains in the form of particles, material equivalent to Na_2O, 1.5 per cent.; CaO, 1.0 per cent.; F, 1.6 per cent.

These amounts are clearly only a small proportion of the total concentrations of these constituents, and yet a reduction of any one results immediately in a marked diminution in opacity. Many more data are needed before it will be possible to compute the concentrations at the equilibrium state of CaF_2, NaF, Na_2O, CaO and F, although such fundamental work as that reviewed to-night is leading towards that goal. Manufacturers of opal glass are following closely the implications of the researches of these workers on so-called "pure" research.

We also found, as has been confirmed on many occasions since, that the form in which the fluorine was introduced was important. Some fluorine compounds are more liable to lose their fluorine in the early stages of melting than others, with the result that the glass is not as dense for a given amount of fluorine in the batch, and since fluorine compounds are relatively expensive, this is a serious consideration. The pot attack also varies with the fluorine compound, but it is of interest to note that the mixtures finally developed are little more corrosive for pots and blocks than ordinary mixtures used for the manufacture of globes. This is a very important practical point, since the absorption of opal glass is closely associated with its iron content. A very interesting series of experiments was carried out by Gehlhoff and Thomas[3] in order to determine how far the absorption of the matrix affected the total light absorped in opal spheres. By adding to the matrix colouring materials whose absorption was known, the effect on the absorption of opal glasses coloured with the same material was measured. From a comparison of the two sets of results, these experimenters were able to show that the mean length of path in an opal glass was about four times that of the actual thickness of the glass, owing to the devious route followed by the light in travelling through the mass of particles. In their particular specimens in which the total light absorption for spheres was about 15 per cent., they found that about 5 per cent. of this was due to the absorption in the matrix, and the other 10 per cent. due to absorption in the opalizing particles. If, hwever, one-third of the absorption is capable of removal by careful attention to the purity of the materials, this is a very substantial advantage. It is also well to remember that the inevitable greenish tinge consequent in the presence of iron compounds is more noticeable when viewed against a background of white light due to scattering by the particles. For these reasons the use of a decolouriser is to be avoided as far as possible because of the increase of light absorption caused by its use, and yet the control of iron contamination—always a difficult task—becomes even more important in this type of glass.

Owing to the very considerable variety of shapes needed for lighting purposes, it is impossible to develop automatic methods of manufacture, and therefore globes for lighting purposes are still made by hand methods. These methods of manipulation are well known, and need not be described again here. The testing of opal globes in the warehouse has to be more detailed than for ordinary clear lighting glassware. Every opal globe made is tested for filament visibility as a matter of routine. This is not so much because of variations in material as because of variations in manufacture, and in the earlier days many globes had to be rejected owing to the filament being visible through the thinner portions of the globe. As experience increased this difficulty largely vanished, and to-day it is the exception rather than the rule that any trouble is found in this way. One does not realize in normally well-established manufacture how much a workman depends on eyesight for the control of this work. The process is so rapid, and apparently so automatic, that it is only when men change from a transparent to a semi- or completely opaque material that one finds that a new technique is required. Much

[2] Ryde and Yates, "Opal Glass." J. Soc. Glass Tech. 1926, 10, 278.

[3] Gehlhoff and Thomas. Z. Tech. Physick. 1928, 9, 173.

practice is needed to enable articles of a uniform thickness to be made in the latter case.

Comparatively recently we have introduced as a routine operation in the warehouse measurements of the light-output ratio of globes. These measurements are carried out in two large photometric cubes under comparative conditions. In one a globe is used which has been found to give the minimum transmission allowable under a standard test, and globes are tested against this as a sub-standard. The girl who does the tests does not make an estimate of the total transmission, but merely finds whether the light-output ratio is greater for the globe under test than for the standard. A predetermined proportion of globes of any pattern made is examined in this way.

In addition to the glass required for electrical work, we were called upon to provide glasses of higher thermal endurance for gas lighting. It was known from experience with clear globes what figure of thermal endurance was desirable in order to give satisfaction for this purpose. The figure referred to, of course, is that adopted by the Society of Glass Technology[4] as a provisional standard, as a measure of thermal endurance, and which is simply the temperature difference needed to break a beaker of a specified shape and a specified thickness. For "electrical" opal this was approximately 170°, whereas the figure considered necessary for ordinary gaslighting purposes was about 260°. The only way in which the thermal endurance could be raised was by changing over to a harder borosilicate containing considerably more boric acid, and this, as was mentioned above, immediately decreased the opacity for a given fluorine content. Increasing the fluorine means increase of pot attack and, generally, increased difficulties in manufacture, but it has been possible to provide an opal glass which, while it does not have the same diffusing power as "electrical" opal, is nevertheless sufficiently good in this respect to meet requirements for sources such as gas mantles whose brightness is not as intense as that of an electric filament lamp.

Flashed Opal Glasses.

The fundamental properties needed in order to ensure satisfactory manufacture of a flashed glass have been investigated by a number of people, notably, Professor Turner.[5] Provided that the difference in the annealing temperature of the two glasses is not too great, the deciding factor is the difference in the coefficients of expansion of the two glasses. Experiments have shown that the coefficient of expansion of opal glass is not constant, but depends apparently on the rate of crystal growth, but certainly on the duration of the found and the degree of opacity developed with a given mixture. In order, therefore, to make a satisfactory flashed opal, attention to founding conditions is extremely important. In cases like this, obviously the mere measurement of the coefficient of expansion between two temperatures is insufficient, and it becomes necessary to devise means of estimating the tolerance under normal founding conditions. This difficulty was overcome by a theoretical investigation as to the curvature introduced in a sheet by the difference of length consequent on cooling from a high temperature measured, of course, on the annealed glass. Then, by cutting a thin strip from a flashed sheet, it was possible to estimate closely the difference in effective coefficient of expansion between the two glasses and to apply a correction to the mixture. At the present time the flatness of flashed opal sheet is actually better than that of many simpler combinations.

[4] "A Provisional Standard Test for the Thermal Endurance of Glass." Proc. Soc. Glass Tech. 1030, 14, 160.

[5] Winks & Turner. J. Soc. Glass Tech. 1928, 12, 161. Körrn. Keram. Rund. 1927, 37, 60.

Samples of Various Flash Thickness.

Flashed glasses possess the advantage over "pot" or through-coloured glasses, that the intensity of the colour, or opal, as the case may be, is capable of adjustment from a given batch composition in the same melt by changing the thickness of the flash without changing the thickness of the resultant sheet. This is a real advantage, especially where articles are needed in relatively small quantities.

From the discussion of the effect of absorption in the matrix on the total transmission of an opal glass, it is easy to visualize the difference between the appearance of a coloured opal and a white flashed opal covered with a coloured clear glass. In order that a coloured opal should appear a definite shade by reflected light the matrix colour must be fairly intense, since the light reaching the observer is reflected partly from the depths of the glass, but chiefly from the surface layers where the incident light has not been sufficiently affected to give a definite colour. Thus the reflected light is unsaturated in the colorimetric sense unless the matrix is so deeply coloured as to be almost opaque to transmitted light. If a white opal be flashed on a clear-coloured glass, all the reflected light has travelled through the same thickness of colouring medium, and is more nearly saturated in consequence. The colour by transmitted light is also nearly identical with that of reflected light. Thus results can be obtained with flashed glasses in this way which cannot be achieved by pot metal. Large quantities of these glasses are made in green, yellow, blue and pink for mural decoration, and were used notably in connection with Broadcasting House.

Samples of Coloured Opal.

Very interesting results may be obtained by running thin threads of coloured glass round the opal "post" before covering with clear glass. After manipulation a marbled effect is produced as is shown in the specimens before you. The question of the coefficient of expansion is again vital to success.

Pot Opal Sheet.

Opal glass sheet has been used for many years for such work as glazing shelves, lining ceilings, and so on. The manufacture has been extensive in Belgium, and, until recently, rather spasmodic in this country. Much of the foreign glass showed on examination by transmitted light, and, in bad cases by reflected light, bands of varying opacity. The glass was made by the hand-blowing process, and the "belts" were due to varying degrees of growth of the particles caused by the reheating needed in the blowing process. Small cylinders can usually be made by a "one-swing" process avoiding the necessity of reheating in the "glory hole." Such cylinders did not show the defect. A mixture has, however, recently been developed which is relatively insensitive to the effect of reheating, and sheets sensibly uniform in opacity are now available. A section through a sheet of poor glass shows definitely the effect of the overlapping of the gatherings in the size of particle. We are indebted to

FIG. 1.—A Foreign Sample of Opal Glass showing variation in diffusion.

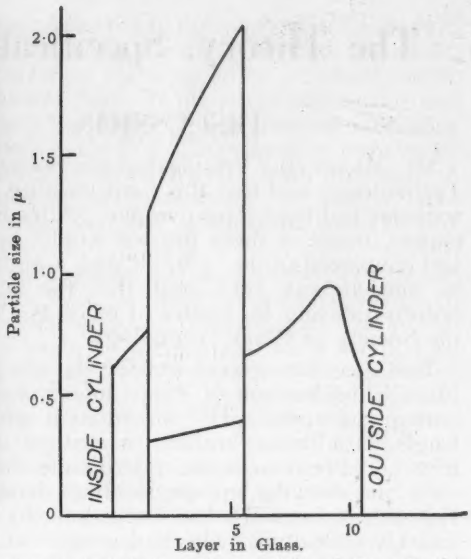

FIG. 3.—British Opal Glass: Relation between Particle Size and Layer in Sheet.

Mr. Dunbar, of the National Physical Laboratory, for this diagram, which illustrates the stage to which such technique has been brought.

Since light absorption is of secondary importance for the purposes for which pot opal is used, substances such as calcium phosphate and tin oxide, which impart opacity readily and cheaply, are usually employed.

DIFFUSALYTE.

The final type of which mention should be made is the type of glass known variously as "Moonstone," "Diffusalyte," "Equiluxo," or "Alabaster." It is characterised in that it allows the filament to be seen as a white hazy patch of light, quite distinct from an ordinary opal. From the work of Ryde and Cooper one would anticipate particles of larger size, and both from the description of opal by Ryde and Yates[6], and from measurements made by Mr. Dunbar, on specimens made by us, one can say that this is a fact. The mean particle diameters in our samples varied from about 3 to 5μ at various depths, and the concentration is about 3×10^7 per c.c. It has been suggested by Ryde and Yates that the particles are really gas bubbles, probably containing SiF_4, but it must be emphasized that a mere trace of fluorine is sufficient to give the desired result, and that the presence of high concentrations of alumina and lead oxide, as well as sulphates, is needed. Admittedly, this does not disprove the suggestion about the nature of the particles, but the fact that a solid nucleus was observed by both authorities seems to render the conclusion dubious. Further, if the particles contain gas, the scattering power can be calculated for a refractive index of 1.00, and the result is that "q" is about 680, whereas the measured value is only 30.

The range of compositions available for glass of this type is restricted, as experience shows that variations in alumina, lead oxide, sodium sulphate and arsenic rapidly alter the diffusing power. It is possible to combine the high transmission of "Diffusalyte" with the whiter appearance of ordinary opals by using appropriate proportions of a normal opal mixture. Such glasses are regularly made to suit special needs, though, in general, the original "Diffusalyte" is preferable for domestic lighting.

[6] *Loc. cit.* pp. 280, 281.

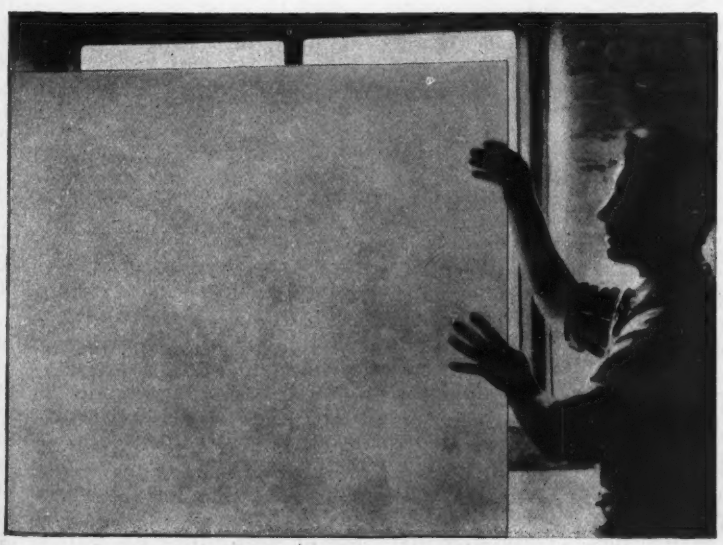

FIG. 2.—New Pot Opal Glass showing uniformity of diffusion.

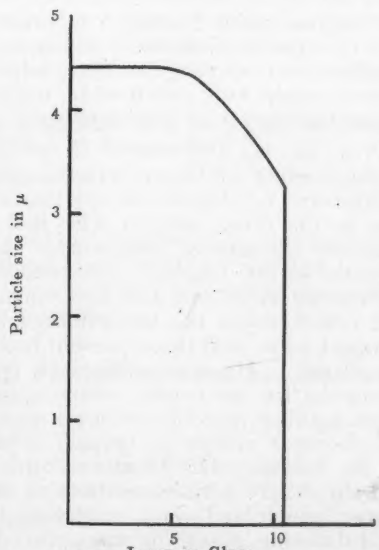

FIG. 4.—Diffusalyte Glass: Relation between Particle Size and Layer in Sheet.

The Theory, Specification and Manufacture of Opal Glasses

DISCUSSION

Mr. MEIGH (the President of the Society of Glass Technology) said that this joint meeting of the two societies had been long overdue. After hearing the papers, many of those present would, he felt sure, feel convinced of the value of such a gathering, and he himself was very glad that the meeting had occurred during his tenure of office as President of the Society of Glass Technology.

This peculiar glass-emulsion known as "opal glass" had become of great importance to illuminating engineers. The information given in Dr. English's address furnished a striking example of what could be done in the way of collecting scientific facts and drawing up specifications based thereon. Equally useful work had been done by Mr. Ryde and his colleagues, who had sought to express in precise mathematical terms the requirements of illuminating engineers in regard to opal glass for purposes of illumination. Glass manufacturers were in the less fortunate position, as revealed by Dr. Hampton, of having to comply with these requirements. He hoped that illuminating engineers would be patient with glass manufacturers, and would not only explain exactly what they were asked to furnish, but would realize the difficulties of doing so. Dr. Hampton had hinted at some of these difficulties. If only agreement on what was needed could be more widely attained it would become feasible to produce more by mass production. He feared that the efforts of illuminating engineers to provide the most economical and efficient source of light had been hindered and hampered by bad glass manufacture. It was doubtless equally true that some of the beautiful creations of glass manufacturers had been ruined by illuminating engineers. They would all leave this meeting with a full recognition that many of the problems with which they were dealing individually were linked together, and that their common efforts of solving such problems would prove a blessing to humanity.

The day was gone when the glass manufacturer could fling all sorts of materials haphazard into his furnace and hope for a desirable result. It was most singular how much of the illuminating glassware used in this country was made abroad. The proportion of British-made glassware in use was still small and there was much leeway to make up.

One final point he might mention in connection with the specification which was being prepared was whether a certain range of glass selected to conform thereto might look excellent by night light, but not appear nearly so well in daylight?

Prof. W. E. S. TURNER, D.Sc. (Hon. Secretary of the Society of Glass Technology), said his first words must be of most sincere thanks and appreciation to the three authors who had given such an excellent account of this work. He felt greatly indebted to Dr. English, as a member of the B.S.I. Committee in its old and new form. Dr. English had boiled down the accumulated material into a compact form, and those present had benefited from his efforts. He was particularly indebted to Dr. Hampton for so readily stepping into the breach when another possible author found himself at the last moment unable to prepare a proposed paper. In Dr. English, Dr. Hampton and Mr. Ryde they had three very active members of the B.S.I. Committee, which has been considering this question of light-diffusing glass. It was a very happy arrangement that they had been induced to take part in the meeting and present their respective points of view.

This material (opal glass) was really quite old, and its manufacture went back at least twenty centuries. He had seen many specimens of such glass in museums. Tin oxide was one of the oldest ingredients for producing opal glass, and had been used since quite early times. But it was only within these last few years that one had acquired a real knowledge of the nature of opal glass.

The power of diffusing light was in reality one of the most intricate and difficult qualities which had been referred to them in the Department of Glass Technology. The task of framing directions enabling manufacturers and others to produce opal glass of the desired quality was by no means easy. It was so easy to fail to state essential conditions.

Manufacturers should have more knowledge of the processes of transmission of light, and illuminating engineers should realize that the manufacture of opal glass is a difficult operation. Great care is needed to maintain a certain constancy. Fluorides, which are used as opacifying agents, are amongst the most corrosive of glass-making materials, and cause constant apprehension with regard to glass-making pots, especially amongst the less-experienced manufacturers. There had been developed a technique by which corrosion could be diminished, but this was attended by other practical difficulties. There was also considerable difficulty in making accurate judgments of time and temperature.

This country was to be congratulated on the way in which it had tackled such a difficult problem, and should feel some pride in the work of Mr. Ryde and his colleagues at Wembley. This work might definitely be described as epoch-making.

The results that Mr. Ryde had presented showed how a knowledge of opal glass could be built up, leading to the possibility of a specification being framed.

There were one or two specific questions he would like to ask. Dr. Hampton had referred to the difficulties involved in the use of opacifying agents and their volatility as a matter of general experience; on the other hand, Gehlhoff and Thomas had apparently found that opacification in the case of fluorides really did not depend on the form in which the fluoride was applied. He would like Dr. Hampton to give his general experience on this matter.

He was not quite clear whether Mr. Ryde had, in his calculations, assumed throughout that he was dealing with fluorides. He had noticed recently quite a number of patents taken out by manufacturers in Czecho-Slovakia. He would like to ask Mr. Ryde if these had come before him for consideration.

In regard to the mechanical strength of the globes, did Mr. Ryde think it desirable actually to specify any specific test of mechanical strength related to the thickness? It might be wise to have a mechanical strength test, but such a test might not be easy to apply.

Dr. Hampton, in his paper, referred to some matters of considerable interest to physicists as well as manufacturers. A case in point was the thermal endurance test for the glass, made apparently by a method that had been adopted as a provisional standard. This method was not necessarily applicable for testing lighting units. He believed that the B.S.I. had a proposed specification for thermal endurance involving the heating of the unit for the period of one hour. This raised rather an important

question, and he wondered whether the test was not rather severe.

In the course of further discussion Mr. L. T. MINCHIN asked Dr. Hampton for information on the size of the particles recommended for opal glassware, and also referred to the proposed method of testing.

Mr. HOWARD LONG remarked that it was all very well to set up a standard, but it might nevertheless prove very difficult to apply it for routine tests.

Mr. F. C. SMITH referred to the heat-resisting test, and stated that his Company had been working on the lines of the specification, and had carried out numerous tests with globes. He did not consider that these tests were unduly severe.

Dr. HAMPTON, in reply, said that Prof. Turner had raised the question of the efficiency of different opacifying materials, and he was not in a position to give any figures, but putting in the fluoride, in various forms, gave much the same results. In regard to Mr. Minchin's question as to the influence of the size of the particles, it was necessary to secure that good general appearance of the exterior, which was such that the direction of the light did not have any appreciable effect. Mr. Long had referred to the proposed routine tests for ordinary working purposes. He did not think that there was any difficulty in carrying out these tests, which were very necessary in order to secure adequate transmission globes.

Dr. ENGLISH referred to the query raised in regard to the clause allowing for different shades in opals. In the specification there would be a definite clause defining transmission. If the shade passed this test it would surely be all right. The thermal endurance tests laid down in the B.S.I. specification were based on data derived from tests which were necessary in order to be sure of maintaining the quality. He was glad to hear that Mr. Smith could confirm their practicability.

Mr. RYDE, replying to a query by Professor Turner, stated that the theory and the curves given in the paper applied to all types of opal. Examination of the particles themselves, as a method of checking quality, would be much more complicated than the methods described. Such examinations had been made for the purpose of checking the complete theory. As regards tests of mechanical strength, he thought that it was clear that some lower limit of globe thickness must be specified, and this had been taken as 1.3 mm., as stated. He agreed that this did not cover the whole question of mechanical strength. Really satisfactory tests for this would be difficult to devise, but the point would be considered. Lastly, as regards the use of one specified type of canopy for the efficiency tests, the reason that a card had been chosen was because it would fit all types of globe and all sizes. It was specified that the card must be white because the photometric errors, due to inaccuracies in setting up, are then much reduced.

Literature on Lighting

(Abstracts of recent articles on Illumination and Photometry in the Technical Press)

Abstracts are classified under the following headings: I, Radiation and General Physics; II, Photometry; III, Sources of Light; IV, Lighting Equipment; V, Applications of Light; VI, Miscellaneous. The following, whose initials appear under the items for which they were responsible, have already assisted in the compilation of abstracts: Miss E. S. Barclay-Smith, Mr. W. Barnett, Mr. S. S. Beggs, Mr. F. J. C. Brookes, Mr. H. Buckley, Mr. L. J. Collier, Mr. H. M. Cotterill, Mr. J. S. Dow, Mr. J. Eck, Dr. S. English, Dr. T. H. Harrison, Mr. C. A. Morton, Mr. G. S. Robinson, Mr. J. M. Waldram, Mr. W. C. M. Whittle and Mr. G. H. Wilson. Abstracts cover the month preceding the date of publication. When desired by readers we will gladly endeavour to obtain copies of journals containing any articles abstracted and will supply them at cost.—ED.

(*Continued from p.* 12, *January*, 1933.)

II.—PHOTOMETRY.

37. A New Photo-cell Photometer. P. R. Gleason.

Rev. Sc. Insts. Vol. 3, *No.* 10, *pp.* 556-560, *October*, 1932.

The sensitive surfaces of two Weston Photronic cells have been combined into a single photometer cell such that a simple null method of photometry is available. The sensitivity of the device has been studied when a sensitive galvanometer was used as indicator, and found to be about five times that of the visual methods. Immediate application to the comparison of two similar light-sources is possible; and by incorporating windows of a suitable filter material comparisons of the luminosity of any two sources is possible without recourse to a flicker photometer. F. J. C. B.

38. The Photronic Illumination Meter. W. N. Goodwin.

Am. Illum. Eng. Soc., Trans., 27, *pp.* 828-835, *December*, 1932.

This new meter uses a Weston Photronic photocell. The cell is directly connected to a moving-coil instrument without any battery, and the unit is direct reading. A full description is given. G. H. W.

39. The Weston Photronic Cell in Optical Measurements. G. A. Shook and B. J. Scrivener.

Rev. Sc. Insts., Vol. 3, *No.* 10, *pp.* 553-555 *October*, 1932.

Photo-electric apparatus is described for the measurement of reflection factors, gloss, and the concentration of coloured or turbid solutions.

F. J. C. B.

40. Action of a Magnetic Field on a Gasfilled Photoelectric Cell. P. Fourmarier.

Comptes Rendus, 195, *pp.* 1387-9, *December 27th*, 1932.

A magnetic field perpendicular to the electronic flux in a cell reduces the photo-electric current. The author studies this effect both for steady and sudden illuminations of the cell. S. S. B.

41. International Photometric Units and Standards. Committee.

Am. Illum. Eng. Soc., Trans., 27, *pp.* 738-751.

Deals fully with the international position on the questions of the primary standard of light, the unit of light, and a general method of photometry. An appendix gives a specification for the proposed primary of light. G. H. W.

42. A Spectrograph of Great Intensity.
Journal of Scientific Instruments, Vol. IX, No. 10, *p.* 328.

This spectrograph was designed by Dr. A. C. S. van Heel. The intensity of the emerging light is sufficient to allow a photograph to be taken in a very short time, or the spectrum of not too weak sources to be investigated by means of a vacuum thermocouple. By means of the eyepiece, lines at distances of 0.02 mm. can be separated visually, e.g., the two D lines of sodium at 5890A and 5896A may be separated. W. B.

III.—SOURCES OF LIGHT.

43. Variations in the Luminous Intensity of Incandescent Lamps as a Function of the Variation in Mains Voltage. H. Pecheux.
R.G.E., 32, *pp.* 867-871, *December* 31*st*, 1932.

Discusses the subject mathematically, and gives the results of practical measurements on the relation between the candle-power and voltage of various incandescent lamps. W. C. M. W.

44. Light Production. Anon.
Elect., 109, *p.* 807, *December* 23*rd*, 1932.

A brief description of the principles of light-production from gaseous discharge tubes, derived from papers recently published in Germany, is presented. The author also reviews practical developments, and mentions the combination of the light from incandescent lamps with that from discharge tubes. A photograph of a fitting of this nature is reproduced. C. A. M.

45. Sodium Vapour Lamps. H. Duschnitz.
Licht u. Lampe, 26, *p.* 397, 1932.

A description of various forms of construction of sodium vapour lamps and their methods of working is given. Modifications of the lamps for different applications are also described. E. S. B-S.

46. The Mercury Arc as an Actinic Stroboscopic Light Source. H. E. Edgerton and K. T. Germeshausen.
Rev. Sc. Insts., Vol. III, No. 10, *pp.* 535-542, *October*, 1932.

Stroboscopic light-sources capable of producing sufficient actinic light to take a photograph with a single flash are described. The duration of the main flash is of the order of 10^{-5} second, depending upon the circuit arrangements and the temperature of the light-pulse tube. The light has been very useful for obtaining stroboscopic motion pictures of the surges of gas-engine valve springs, vibrations of mechanisms, etc. 4,200 pictures per second have been taken. The fundamental idea is to discharge considerable electrical energy into a mercury-arc tube by means of an electrical transient, which is usually obtained from a condenser discharge. Several methods of actuating the flash are described. F. J. C. B.

47. Combination Lighting. H. G. Schiller.
Light, 2, *No.* 10, *p.* 29; *Year end*, 1932.

Particulars and a photograph are given of a ceiling fitting that combines the use of gaseous vapour and incandescent lamps. A 300-watt lamp is located in the centre of a circular mercury-vapour tube. The total rating is approximately 750 watts. The transformer is housed in the canopy. C. A. M.

V.—APPLICATIONS OF LIGHT.

48. The Year's Progress in Illumination. W. C. Brown.
Am. Illum. Eng. Soc., Trans., 27, *pp.* 725-737, *November*, 1932.

Progress is recorded under 15 headings. G. H. W.

49. The Human Seeing Machine. M. Luckiesh and F. K. Moss.
Am. Illum. Eng. Soc., Trans., 27, *pp.* 699-722, *November*, 1932.

Considers the science of seeing as a triple complexity consisting of external factors, the visual sense, and the psycho-physiological effects. A reading test under various levels of illumination to determine nervous muscular tension showed that this factor decreased with increasing illumination. G. H. W.

50. Lighting the Mall. Anon.
Elect., 109, *p.* 850, *December* 30*th*, 1932.

Details are given of the new lighting installation in the Mall. The constant potential-series circuit, originally installed for the old arc-lamp system, is utilized and gasfilled lamps of special manufacture, rated at 1250 watts, are burnt in groups of four in series across 400 volts. Illumination values now obtained are approximately four times those obtained originally. C. A. M.

51. Economic Value of Good Street Lighting. F. C. Caldwell.
Am. Illum. Eng. Soc., Trans., 27, *pp.* 808-821, *December*, 1932.

Statistics of street accidents and crime are analysed with the object of determining the monetary value to the country of good street lighting. A considerable value is found. G. H. W.

52. Light and Architecture. Anon.
Am. Illum. Eng. Soc., Trans., 27, *pp.* 679-687, *November* 1932; *pp.* 769-778, *December*, 1932.

Illustrated descriptions of sixteen modern lighting installations. G. H. W.

53. Illumination from Laylights. H. Stöckel.
Licht u. Lampe, No. 1, *p.* 7, 1933.

The author discusses the use of different glasses for use as laylights. Tables are given which enable the total lamp wattage to be determined for rooms of various sizes. G. H. W.

54. Bank Lighting. J. W. Fleming.
Light, 2, *No.* 10, *pp.* 20-21; *Year end*, 1932.

One feature of the improvement of general lighting in a bank in Buffalo is the use of trough equipment fitted to the top of the bank screening. Illumination values of 30 foot-candles are obtained on the tellers' counters. C. A. M.

55. Illumination and Ventilation in the Factory. Anon.
World Power, 19, *p.* 17, *January*, 1933.

A record of work done by the National Institute of Industrial Psychology includes instances of the effect of lighting improvements in Post Office work. The greatest speed of sorting was obtained with an illumination of eight foot-candles. A maximum surface brightness of opal glassware in the lighting unit of 2.5 candles per square inch is recommended in this connection. C. A. M.

56. Different Lighting System for Coal Mines. Anon.
El. World, 100, *p.* 831, *December* 17*th*, 1932.

An outline is given of the new system of series lighting for coal mines recently envisaged by Prof. Cramp. W. C. M. W.

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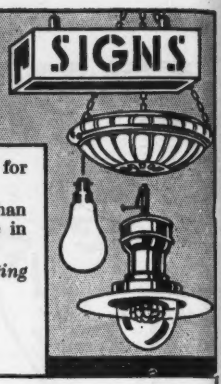

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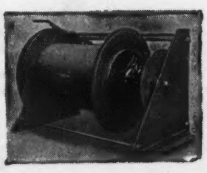
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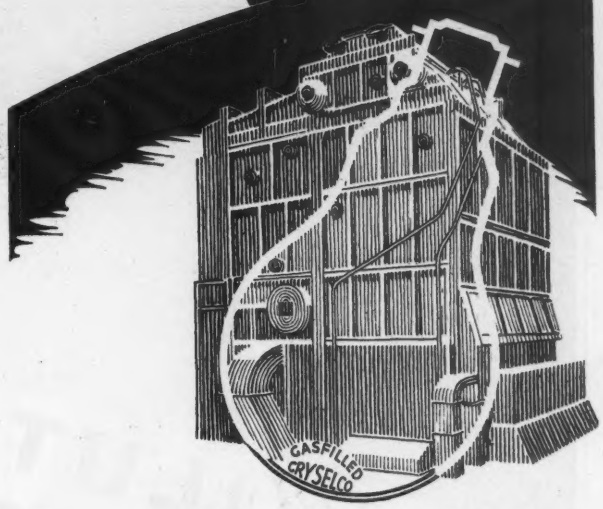

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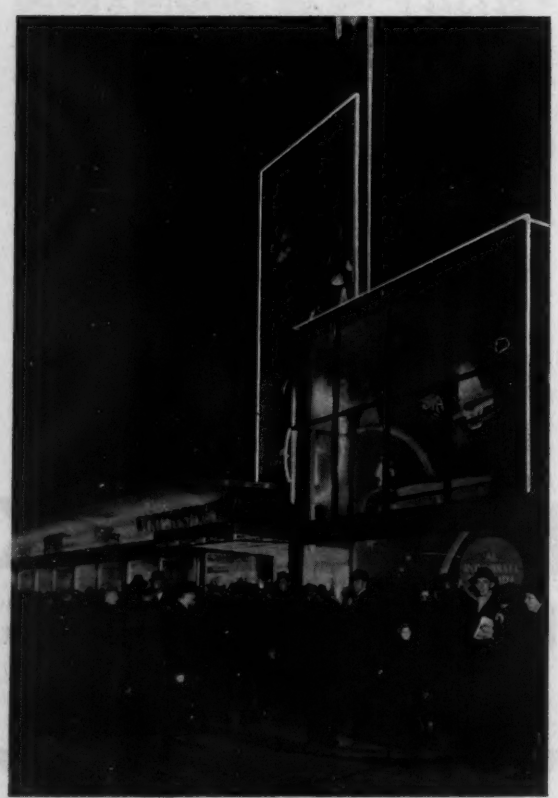

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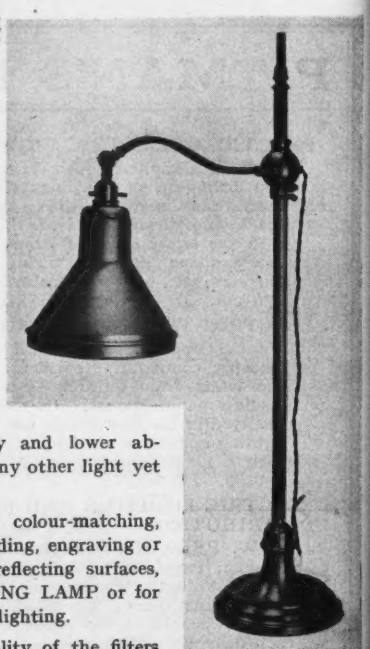

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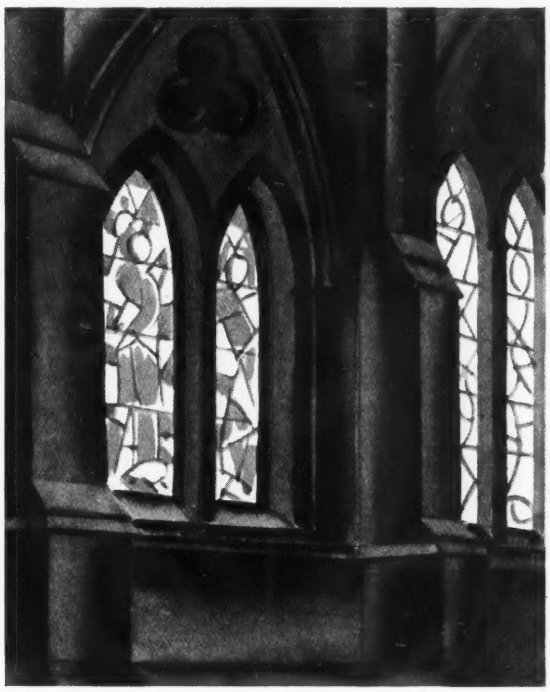

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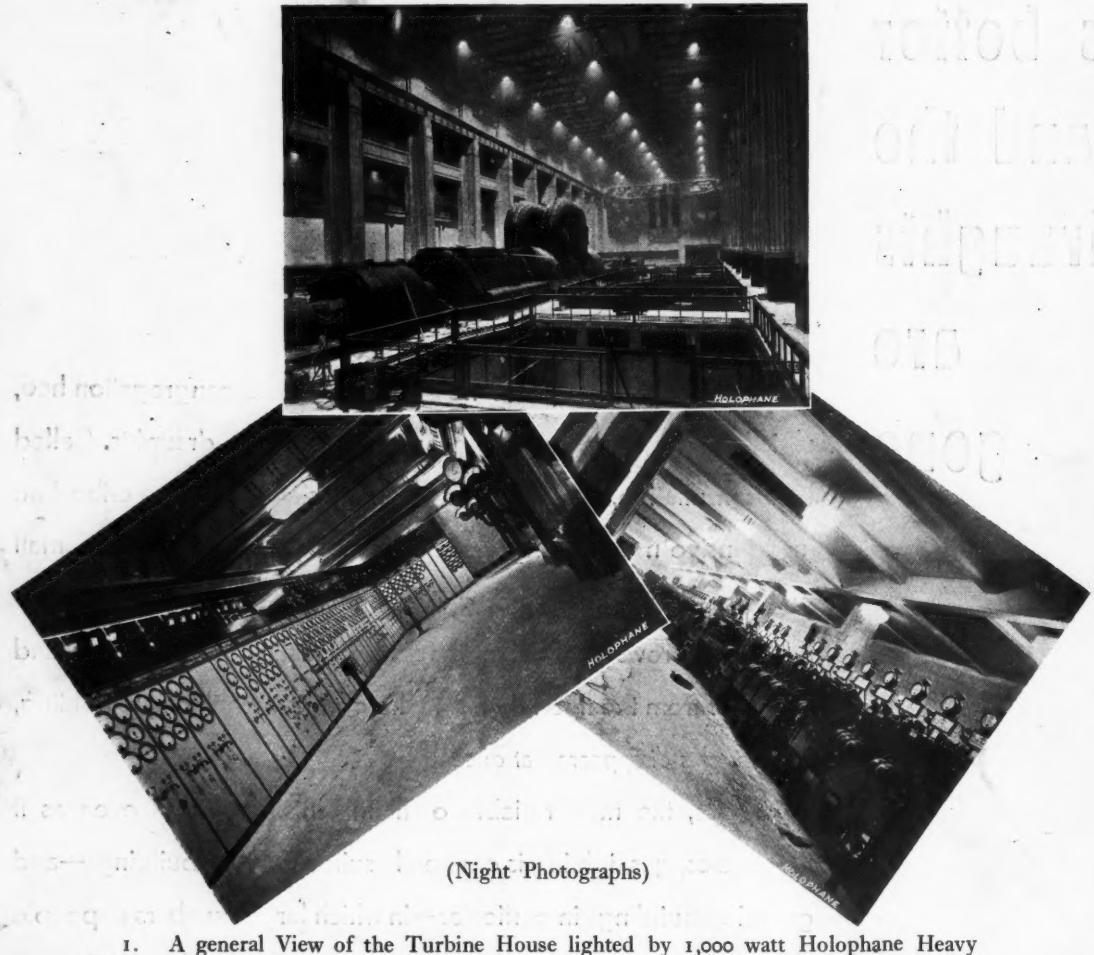

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